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The hydrography of the estuary of the River Blackwater

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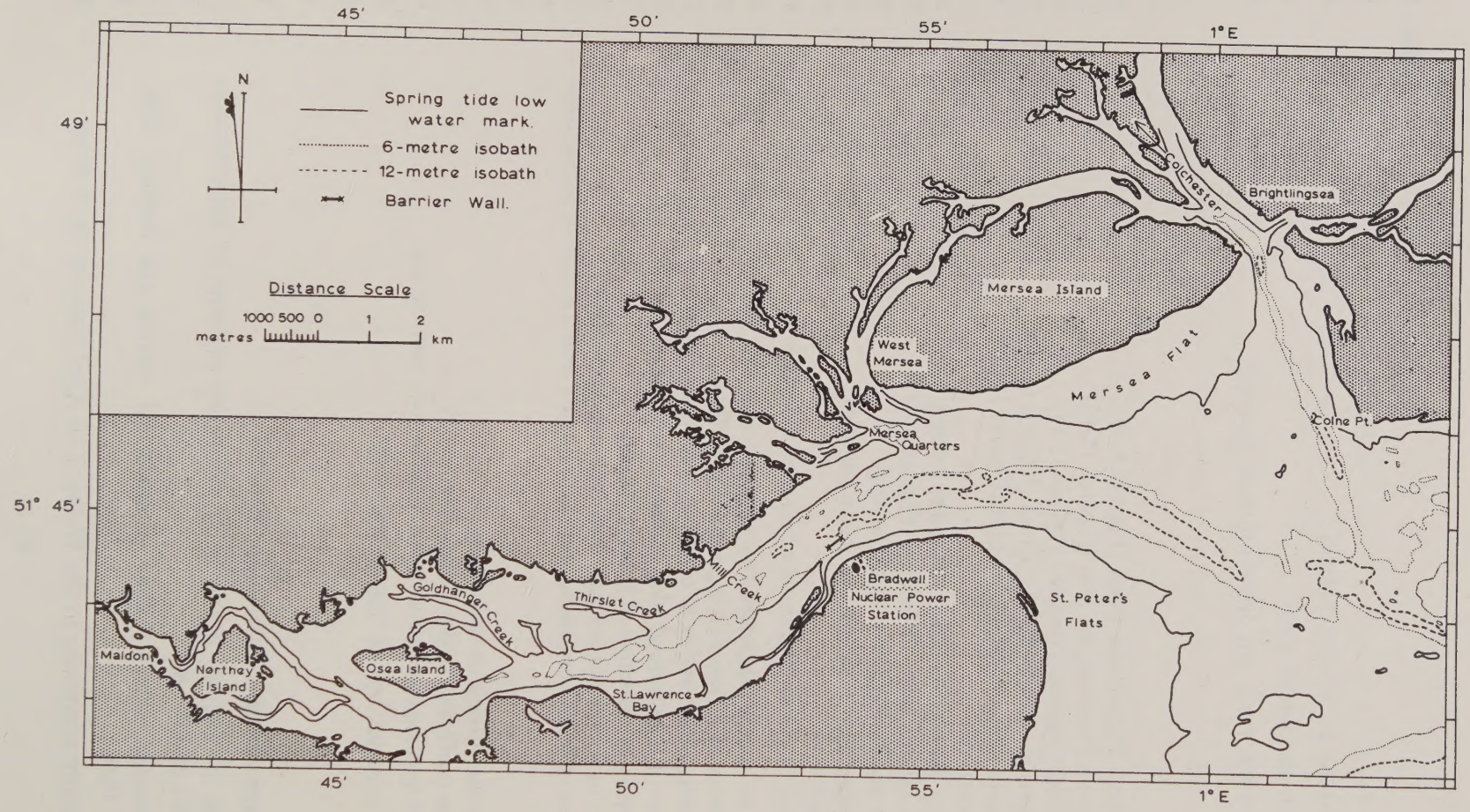
Fig. 1. *General outline of the Blackwater estuary.*



The hydrography of the estuary of the River Blackwater

SYNOPSIS

THE results of various surveys carried out in the estuary of the River Blackwater indicate that this estuary is of the vertically homogeneous type. River flow into the estuary is small and the main water movements are associated with the comparatively large tidal oscillation. Although some evidence of horizontal stratification is found, together with a suggestion of a residual anti-clockwise circulation such as might result from Coriolis force, this evidence is inconclusive for the region near the Bradwell nuclear power station. A feature of the water movement is the vertical current shear produced as water floods on to the mud flats, and this current shear appears to play an important part in the overall mixing process.

In summer the river flow is of the same order as water loss resulting from evaporation, and there is a tendency for the salinity of the estuarine waters to approach or exceed that of the open sea.

Various attempts to estimate the degree of mixing between the estuary and the sea suggest that between 1% and 5% of the high-water volume is lost to the sea on each tide.

INTRODUCTION

WHEN it was decided by the Central Electricity Generating Board (C.E.G.B.) to build a nuclear power station near Bradwell Waterside on the estuary of the River Blackwater, the local fishermen expressed concern as to the effect that the operation of the station might have on the environment of the estuary as regards fishing, and especially as regards the oyster farming which is relatively important in this area. It was then agreed that the C.E.G.B. and the Ministry of Agriculture, Fisheries and Food (M.A.F.F.) should look into this problem. This report presents and discusses the results achieved up to the time of writing, from data collected on a number of hydrographic surveys of the estuary which were carried out by the Hydrographic Section of the Fisheries Laboratory, Lowestoft, over the period February 1960 to March 1962.

The estuary of the River Blackwater is situated in Essex about 32 km north of the estuary of the River Thames. At its mouth it is about 8 km wide and it narrows down to a small river at Maldon, a town about 26 km upstream from the mouth. There are two main channels in the whole estuary system, the major one being that of the Blackwater which flows from the west and from Maldon, the other being the River Colne which flows from the north and from Colchester. The channel of interest to us here is that of the Blackwater, since very little work has been done on the Colne as yet. The channel of the Blackwater is well defined and has a maximum depth of about 20 metres; at low water it narrows in width approximately linearly with distance from the mouth, but at high water extensive mud banks are covered and creeks filled so that it becomes very complicated in outline.

The Bradwell nuclear power station is situated on the south shore of the estuary at a point where the high-water channel is 1 · 8 km wide and the low-water channel 1 · 1 km wide, the mud banks here not being very extensive. The spring tidal range at this point is approximately 5 metres. Just offshore from the power station, at a position where the very steep southern side of the river channel begins to level out, are situated the intake and outfall orifices for the cooling water used in the power station. These two orifices are separated one from the other in the transverse direction of the channel by a steel "barrier wall" which is 805 feet long and runs along the line of the river channel.

A general outline of the estuary is shown in Figure 1, which illustrates the extent of the mud flats. the 6-metre and 12-metre isobaths, the creek systems, and the positions of the power station and the barrier wall. This outline is taken from Admiralty Chart No. 3741.

In terms of the general classification of estuaries suggested by Cameron and Pritchard (1963) the Blackwater appears to be of the vertically homogeneous type. The fresh water enters at the upper extremity of the tidal part of the river which is at Beeleigh Grange, about 1·5 km above Maldon. This fresh water flows from the Rivers Blackwater, Chelmer and Ter, and the flow rate at the time of the surveys was such that a typical value of the ratio between the volume of water entering the estuary at Beeleigh Grange during the period of one spring tide to that entering and leaving the estuary mouth as tidal flow during one tide was approximately 1:4000. The relative volumes of water contained in the estuary for typical tidal situations, together with comparable values of the river flow per tide, are given in Table 10, Appendix III. The fact that the mean summer velocity past the power station corresponding to the river flow would be of the order of 10^{-3} cm/sec, compared with a peak tidal velocity at this section of the order of 10^{2}cm/sec, may help to illustrate the importance of the river flow relative to tidal flow. Indeed it seems probable that at times during the summer months evaporation will exceed the river flow, producing an overall residual inflow over the mouth of the estuary. This situation is illustrated in Figure 21, which shows that during August 1961 the salinity at high water was almost constant along a considerable length of the estuary. There can be little doubt of the importance of evaporation when considering the hydrography of the Blackwater, and much of this will take place over the extensive mud flats which are covered at some parts of the tidal cycle. These flats play another important role in that they produce significant changes in the flow of water in both the vertical and horizontal directions.

SUMMARY
OF THE SURVEYS MADE BY M.A.F.F. VESSELS

THE information upon which this account is based was obtained during the following operations:

		No. of surveys	No. of boats
1st Operation	February 1960	1	1
2nd Operation	March 1960	1	2
3rd Operation	August 1961	3	5
4th Operation	November 1961	5	3
5th Operation	February/March 1962	2	5

Of these five operations the first two were intended principally as preliminary surveys carried out so that the major surveys of 1961-62 could be planned to the best advantage. Results from the earlier surveys have, however, been included where these appear relevant and helpful to the establishment of the conditions in the estuary. The first survey was carried out by R. V. *JASSA* which moved from station to station over a total period of 29 hours; the second was worked by R. V.s *JASSA* and *ONAWAY*, and this time operations continued over a period of one week. The third operation was carried out in three parts which will be referred to as Surveys A1, A2 and A3 (see Table 1). In Surveys A1 and A2 five vessels took part, anchored at positions along the estuary (see Figure 2) which were selected after consulting the results of surface float tests which had been made by members of the C.E.G.B. and the M.A.F.F. laboratory at Burnham-on-Crouch. It was arranged that each vessel should occupy its station for two tidal periods (25 hours) on each of two occasions, once during spring tides (A1) and once during neap tides (A2). These surveys were timed to take place at a period when it was to be expected that the run-off from

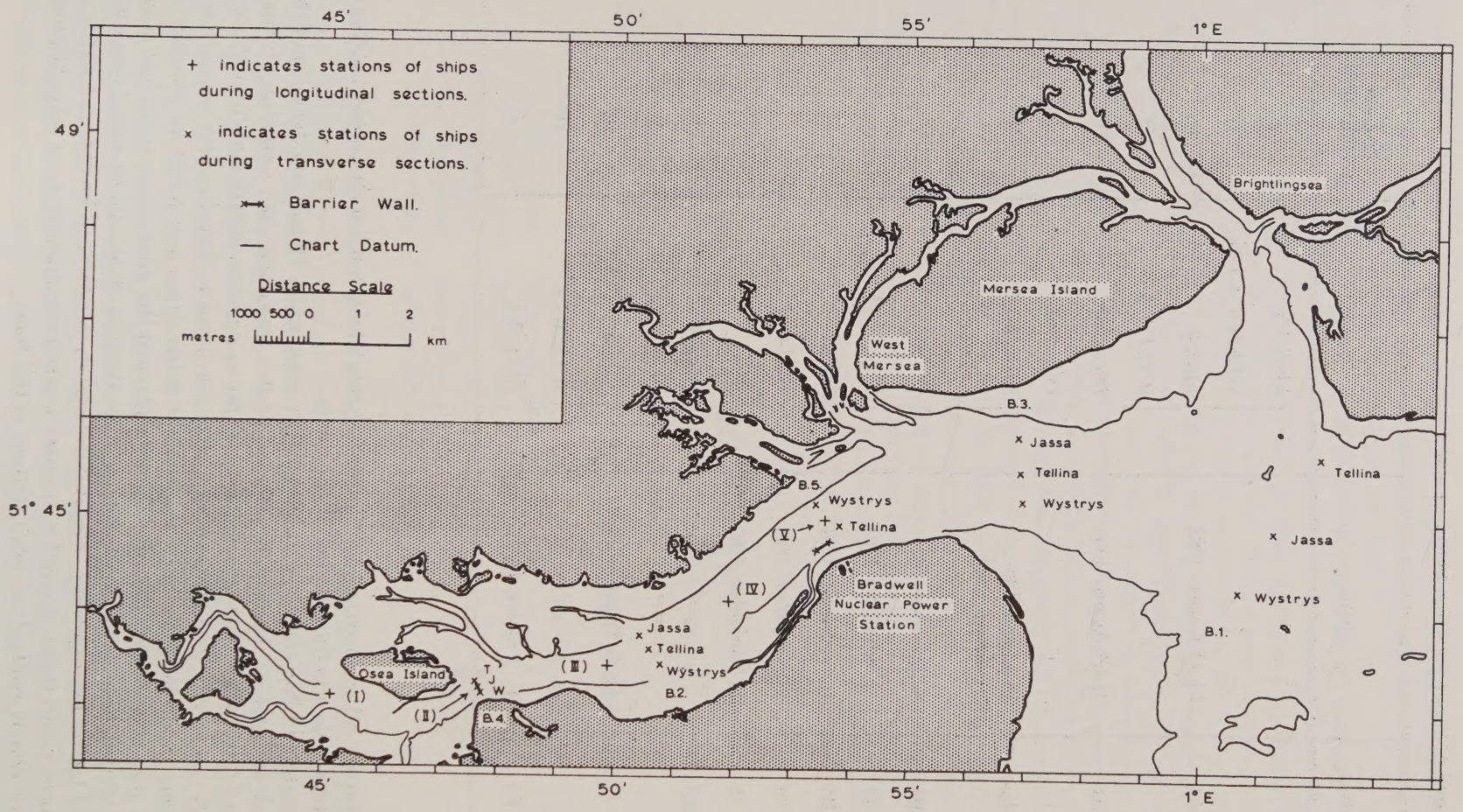
Table 1. *Summary of vessels and positions for Operations* 3, 4 *and* 5

Operation	Survey	Dates	Vessels	Position (see Figure 2)
3	A1	14–15 August 1961	*EVELYN*	I
			MERSEA LASS	II
			JASSA	III
			WYSTRYS	IV
	A2	21–22 August 1961	*TELLINA*	V
	A3	18 August 1961	*TELLINA*	
			WYSTRYS	
			JASSA	
4	B1	9 November 1961		
	B2	11 November 1961	*WYSTRYS*	
	B3	16 November 1961	*JASSA*	
	B4	17 November 1961	*TELLINA*	
	B5	18 November 1961		
5	C1	20–21 February 1962	*SALLIE*	I
			CLUARAN	II
			JASSA	III
			WYSTRYS	IV
	C2	1– 2 March 1962	*TELLINA*	V

the land would be small. Survey A3 was carried out by three vessels which worked the transect across the river in the vicinity of the power station for a period of 12½ hours.

During the fourth operation, in November 1961, five surveys were made. These took the form of three vessels anchored in line abreast across the estuary on each of five transects, each vessel occupying its station over a period of one tidal cycle. The transects were, as far as possible, distributed throughout the whole length of the estuary. As can be seen these surveys were not timed to coincide with any particular tidal situation, for they were made in order to reveal how the water types and water movements vary across the estuary. By the time these November surveys were planned the preliminary work had already indicated a high degree of vertical homogeneity; in such estuaries the type of circulation found is markedly dependent on the degree of lateral homogeneity. Whilst it is certainly desirable to be able to compare the results of working one transect with those of another transect worked simultaneously, it was not possible to do so with the number of vessels available to work stations at this time.

Fig. 2. *Outline of the Blackwater estuary, showing the stations occupied.*



The surveys of the fifth operation (C1 and C2) worked the same station positions as in A1 and A2, but were made during February-March 1962 when it was to be expected that the land drainage would be high. By comparing these results with those of Surveys A1 and A2 it is possible to get an idea of the differences in the circulation pattern within the estuary for high and low rates of run-off, respectively. Survey C1 was made during a spring tide and C2 during a neap tide.

The positions of the stations worked in the three sets of surveys are shown in Figure 2. All the boats used are small inshore fishing or research vessels. The stations worked on Surveys A1, A2, C1 and C2 were positioned in mid-stream and were upstream from the power station site, at a distance apart of between 2·5 km and 3·0 km, with *TELLINA* working approximately opposite the power station and the other vessels occupying the upstream stations in the order given in Table 1. *EVELYN* and *SALLIE*, therefore, occupied a station situated just upstream from Osea Island.

The transects worked during Surveys B were positioned between 2·5 km and 4 km apart so that the extreme ones were at the estuary mouth (Colne Point to St. Peter's Flats) and at the easterly end of Osea Island. Figure 2 shows these transects numbered in the order in which they were worked and not with respect to position, and it also shows the positions of the vessels on station. Only two vessels took part in the working of Survey B5 (the power station transect) because of a mishap which occurred during the previous night, making it impossible for *JASSA* to work on that day.

At the end of the working of these transects an echo- sounder survey of the estuary was made in order to check that no significant changes in the bottom topography had taken place since the Admiralty Chart No. 3741 was made in 1957. This was done by running a zigzag course throughout that part of the length of the main channel of the Blackwater that could be covered by *TELLINA*. No substantial deviations from the chart were detected.

There was very little hindrance to work by traffic along the Blackwater; only an occasional barge goes up to Maldon on the flood tide or returns on the ebb, and all movement of ships occurs at high water, there being very little depth beyond Osea Island at low water. One difficulty, however, arose from the considerable number of tankers, twenty or so, laid up in the estuary approximately between the position of Mersea Quarters and Mill Creek (see Figure 1). These were not anchored fore and aft and tended to swing violently in a wide circle as the tide changed. As a result our stations had to be sited so as to avoid collisions with these ships, and were therefore not always in the best position for studying the hydrography of the estuary. During Operation 5 *TELLINA* had considerable difficulty in finding a position out of range of the swinging tankers, the actual position eventually decided upon being slightly south of that shown in Figure 2.

EXPERIMENTAL METHODS AND EQUIPMENT USED

Positioning of the boats on the stations was accomplished either by using the Decca Navigator System or by taking bearings from prominent landmarks. These methods checked satisfactorily against each other. Another check on positioning which was used was to compare the bearing of landmarks or the Decca positioning with the position relative to the bottom topography. In no case was any serious discrepancy detected. On station each vessel was anchored from the bow only. It is obviously better to anchor the vessel from the bow and stern to avoid errors in observation of current speed as the boat swings on the tide, but when this was attempted *TELLINA* dragged the stern anchor in the full ebb current, which reaches 120-130 cm sec^{-1}, causing a very dangerous situation, so this idea was rejected.

Measurements of temperature, salinity and current velocity were made on each station at depth intervals of two metres between bottom and surface. It was intended that these observations should be made at half-hourly intervals throughout Surveys A1, A2 and B1-B5, and at hourly intervals throughout

Surveys C1 and C2. In fact, because the water was in some cases too deep to be fully sampled at 30-minute intervals, observations at some stations during Surveys A1 and A2 and B1-B5 were made at hourly intervals. Water samples were taken at the same time and for the same depth intervals, and observations of the weather conditions were made.

The instruments used for making the observations were as follows:

Temperature:	M.A.F.F. thermistor unit.
Current velocity:	Kelvin-Hughes Direct Reading Current Meter with Ekman current meter as stand-by.
Salinity:	Wayne-Kerr Portable Salinity/Temperature Bridge.
Wind speed:	Ventimeter or anemometer.
Samples:	Taken in Nansen reversing water bottles.

The salinity of the water samples was assessed by measuring the conductivity, using the M.A.F.F. Shipboard Salinometer at Lowestoft. This machine gives an answer with an overall error of salinity of $\pm 0 \cdot 008^0/_{00}$, compared with one of $0 \cdot 05^0/_{00}$ using the Salinity/Temperature Bridge. In considering the results of the surveys it was found to be possible to use almost exclusively the more accurate salinities obtained by the former method.

SOURCES OF INFORMATION OTHER THAN THE HYDROGRAPHIC SURVEYS

In addition to the information obtained from the various surveys described above, this report makes use of information supplied by the Meteorological Office, values of river flow supplied by the Essex River Authority, salinity and temperature records kept by the C.E.G.B., and some values of salinity recorded at the Galloper Lightvessel.

RESULTS OF THE SURVEYS

WHEN discussing the results of this work it will be helpful to bear in mind especially those features that will have a particular influence on water movement. Fundamental to this is the question of stratification, either vertical or lateral. It is important to realise that if stratification is present it will result in advective forces tending to produce circulation of water within the estuary. Such circulation may be easier to deduce from a study of the salinity and temperature distributions than from direct readings of water velocity using a current meter. This residual flow will be important when considering the exchange between the estuary and the sea, and it seems reasonable that we should first examine the results in order to determine the degree of vertical stratification that is typical of the Blackwater estuary.

VERTICAL STRATIFICATION

Operations 3 and 5 were planned to reveal the state of vertical stratification along the length of the estuary under conditions of low and high rates of run-off and at times of spring and neap tides. The results of this work are illustrated in Figures 3 and 4, which show the salinity distributions at two-hourly intervals for Surveys A1 and C1, and Figures 6 and 7, which show the temperature distributions (at times of low and high water) for the same surveys. Thus, in presenting these results, attention has been centred upon Surveys A1 and C1. It seemed that more was to be learned by concentrating on the variation in conditions over one tidal cycle than by attempting to illustrate differences between spring and neap tide conditions which, in this context, appeared to be of minor importance.

In the August survey high water occurred at mid-afternoon and we see from Figure 3 (i) that salinity was substantially constant over the seaward half of the estuary, the only variation consisting of a maximum in the vicinity of *JASSA*, which is thought to be a result of evaporation; we find a similar maximum at this time in the temperature distribution (Figure 6 (ii)). At the next high water, however, in the early hours of the following morning, no maxima of salinity or temperature were found; the salinity showed a gradual increase towards the sea (Figure 3 (vii)) and the temperature was in fact almost constant throughout the region. There is a clear indication here that evaporation plays an important part in the working of the estuary.

Very little vertical stratification was indicated by the results of the August surveys. In February and March, when Surveys C1 and C2 were made, again very little vertical stratification was indicated over most of the tidal cycle, but some was now evident at about low water in the upper reaches of the estuary (Figures 4 (i) and (ii), and 5 (ii) and (iii)). It is probably significant that the river flow six days before Survey C1 was markedly above average (Figure 8). This peak flow was approximately 40.10^4 m^3 per day, corresponding to a mean monthly flow of approximately 1100.10^4 m^3. During the period between the Surveys C1 and C2 the river flow remained at a fairly steady value just below the average for that month. In comparing the results of these two surveys it may be useful to compare the vertical gradients of salinity recorded near the head of the estuary at low water. For the two surveys C1 and C2 these gradients were $3 \cdot 16^0/_{00}$ metre^{-1} and $1 \cdot 78^0/_{00}$ metre $^{-1}$ respectively, both indicating a significant degree of vertical stratification. It therefore appears that for a river flow corresponding to the mean value at this time (approximately 700.10^4 m^3 per month) we should expect some degree of vertical stratification near the head of the estuary at low water. River flows appreciably in excess of this value may be expected to produce some stratification further down the estuary and for greater portions of the tidal cycle than those indicated by the results of Operation 5. Total monthly flows from the Blackwater and Chelmer for 1960-65 are given in Table 2, and these figures reflect the relatively large volumes that are now abstracted for water supply purposes. It will be seen that the flow in February 1962 was quite high compared with more recent monthly values.

Fig. 3. *Distribution of salinity* ($^0/_{00}$) *observed along the length of the estuary during Survey A*1, (i) *at high water (mid-afternoon;* (ii) *two hours after high water;* (iii) *four hours after high water;*

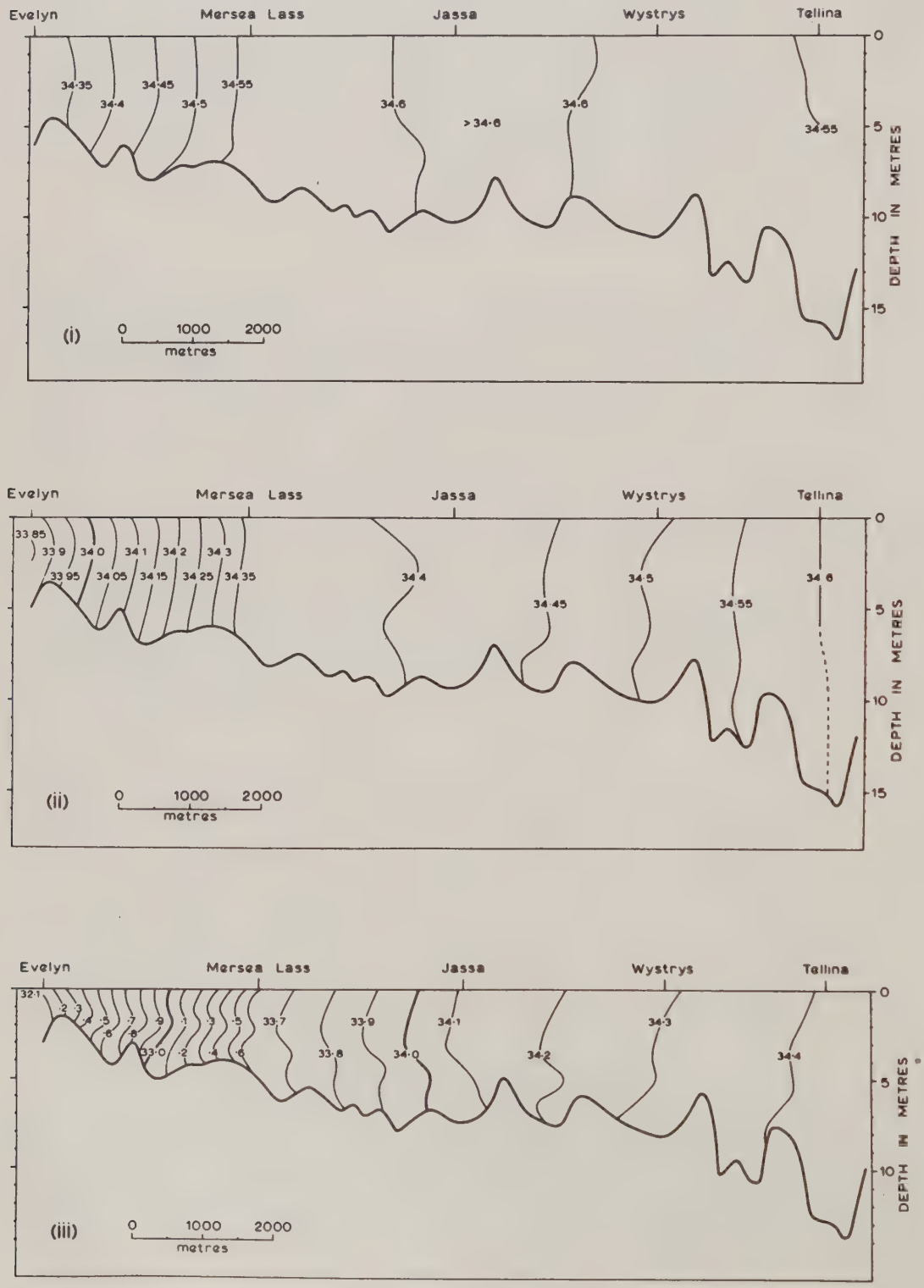
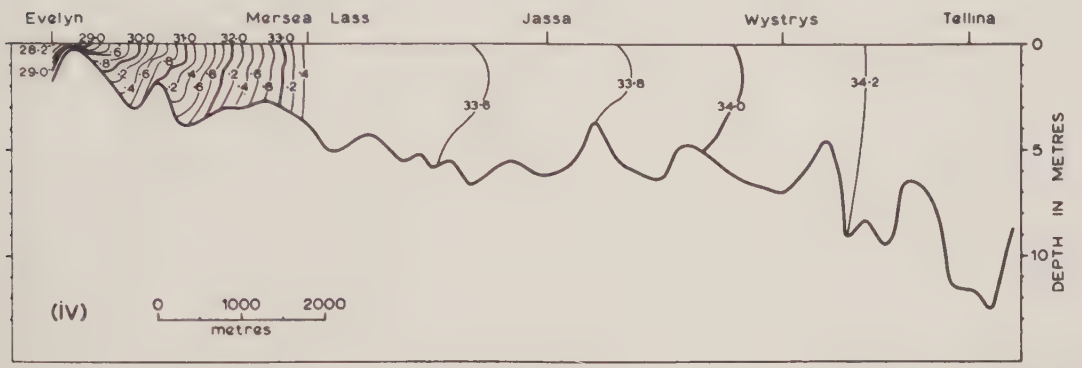
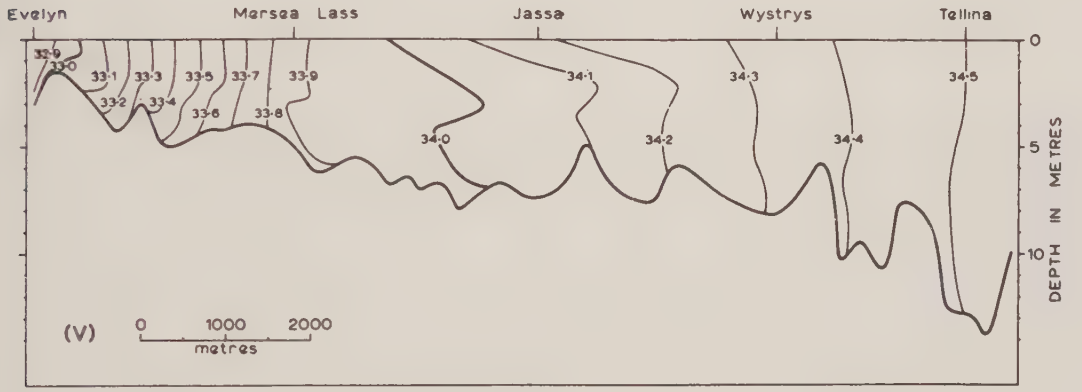


Fig. 3—*continued* (iv) *at low water;* (v) *four hours before high water;* (vi) *two hours before high water;*





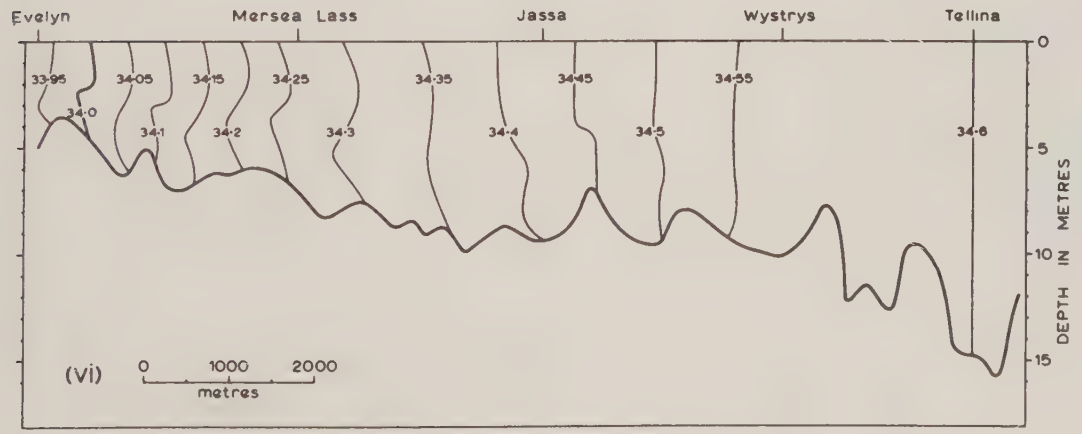
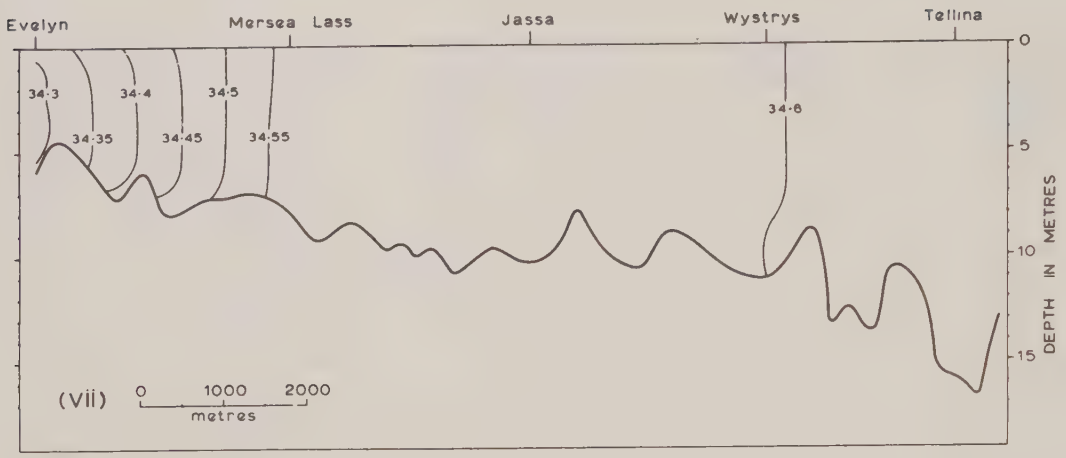


Fig. 3—*continued* (vii) *at high water (night-time).*



We may therefore conclude that vertical stratification in the estuary is slight at almost all times and places, but that during periods of exceptionally high-run-off some stratification may be expected, particularly towards the head of the estuary.

The connection between stratification and a possible residual circulation of water has already been stated and it is this possibility which provides the main interest in the above discussion. A more direct way of investigating any residual circulation of water between the estuary and the sea could, in principle, be based on the current measurements. The method of analysis involved is described later in the section 'Calculation of residual flow from current meter readings'. It is sufficient at this stage to say that for the most seaward station of Operations 3 and 5 this calculation was performed, both using results covering the total depth of the water, and also those for only the upper 0·45 of the total depth. It was hoped that this procedure would reveal any tendency for the residual flow near the surface to differ appreciably from that near the bottom. The results of these calculations are given in Table 3 where it is seen that the greatest difference between the residual water movement near the surface and that at depth was found during Survey C1. The prediction from this survey is for a residual ebb of surface waters and a small residual flood at depth. Whilst it would be unwise to attach too much significance to this one result, the situation predicted is just what would be expected if vertical stratification were beginning to produce a residual circulation in the vertical plane in the estuary. We certainly cannot rule out the possibility that values of river flow of the order of those preceding Survey C1 will result in some residual flow such as has been discussed above.

Table 2. *Total monthly flow from the Rivers Chelmer, Blackwater and Ter into the Blackwater estuary* ($m^3 \times 10^4$)

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1959–60	51	84	757	965	1 172	498	321	299	23	32	111	1 157
1960–61	2 917	3 890	2 927	2 625	1 911	1 360	693	686	111	23	131	144
1961–62	199	251	944	3 034	641	609	826	187	18	215	17	20
1962–63	40	299	145	97	22	1 848	600	430	86	65	53	47
1963–64	23	1 336	220	251	178	2 018	1 317	172	351	18	93	61
1964–65	60	83	27	74	22	346	98	23	18	206	163	672

Table 3. *Evidence concerning vertical stratification of flow at the mouth of the estuary (Station V) for Operations 3 and 5. The observations were for the upper* 0·45 *and lower* 0·55 *of the total depth ('upper' and 'lower' layers respectively)*

Survey	Calculated water movements during one tidal cycle ($m^3 \times 10^4$)					
	Δ_{EBB}		Δ_{FLOOD}		Residual ebb	
	Upper layer	Lower layer	Upper layer	Lower layer	Upper layer	Lower layer
A1	3·45	3·19	3·72	3·91	−0·3	−0·7
A2	2·56	2·01	3·65	2·43	−1·1	−0·4
C1	3·69	3·45	3·14	3·51	+0·6	−0·1
C2	2·27	2·29	2·43	2·38	−0·2	−0·1

N.B.—The results in the last two columns have been reduced to one place of decimals since it is considered that the second figure has little significance.

Fig. 4. *Distribution of salinity* ($^0/_{00}$) *observed along the length of the estuary during Survey C1,* (i) *at low water;* (ii) *four hours before high water;* (iii) *two hours before high water;*

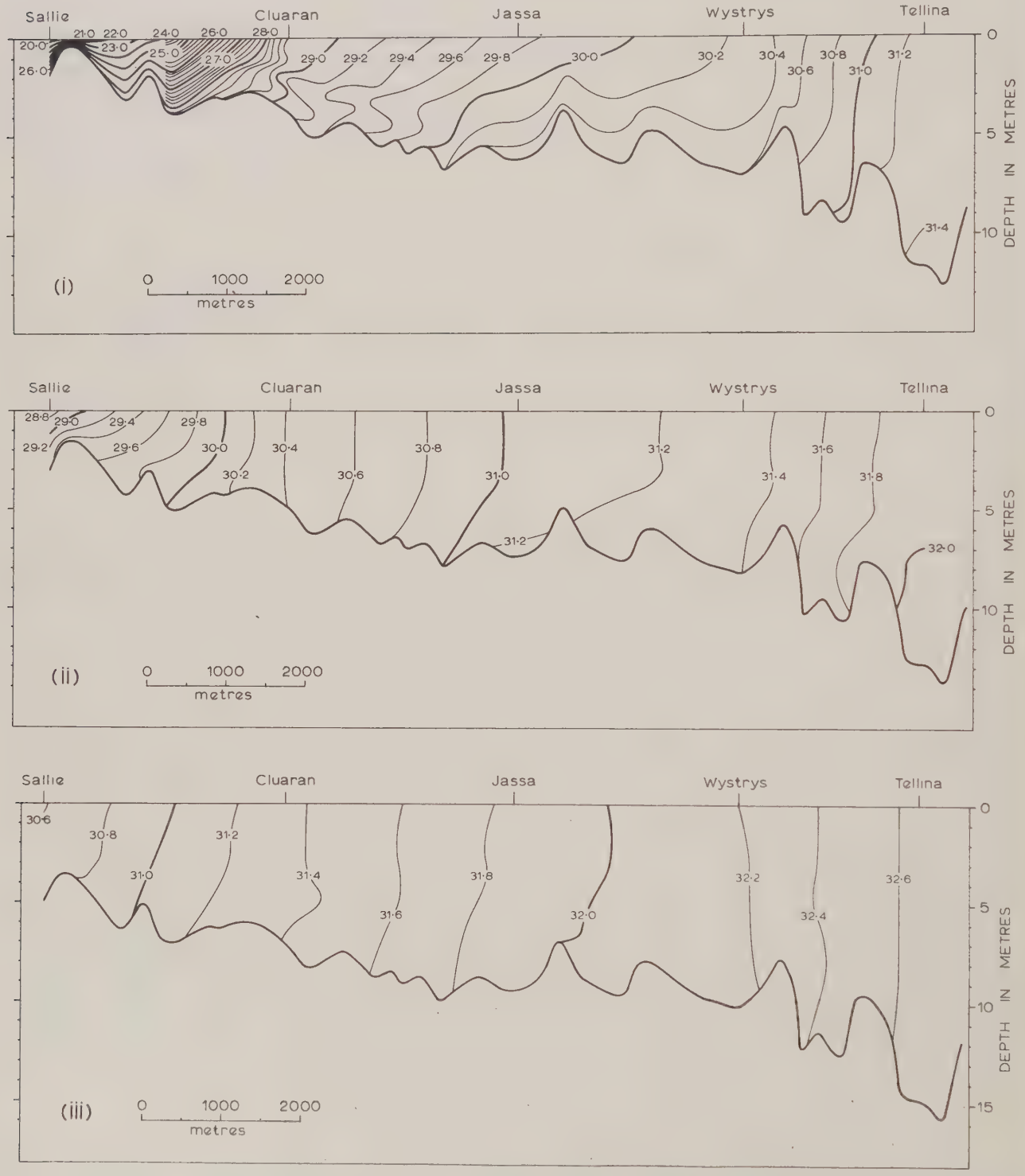


Fig. 4—*continued* (iv) *at high water*; (v) *two hours after high water*; (vi) *four hours after high water.*

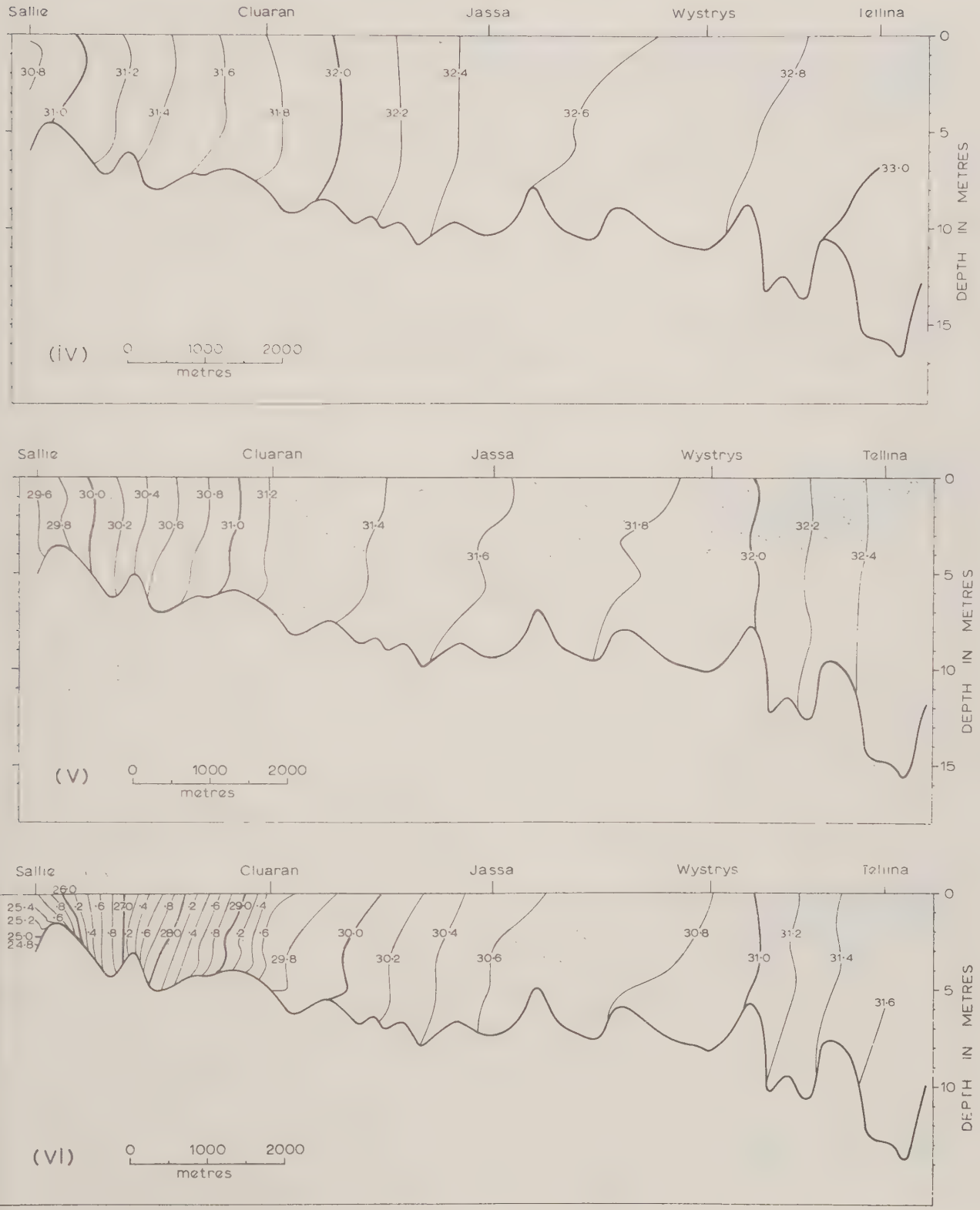


Fig. 5. *Distribution of salinity* ($^0/_{00}$) *observed along the length of the estuary at about low water during Survey C2,* (i) *four hours after high water*; (ii) *at low water*; (iii) *four hours before high water.*

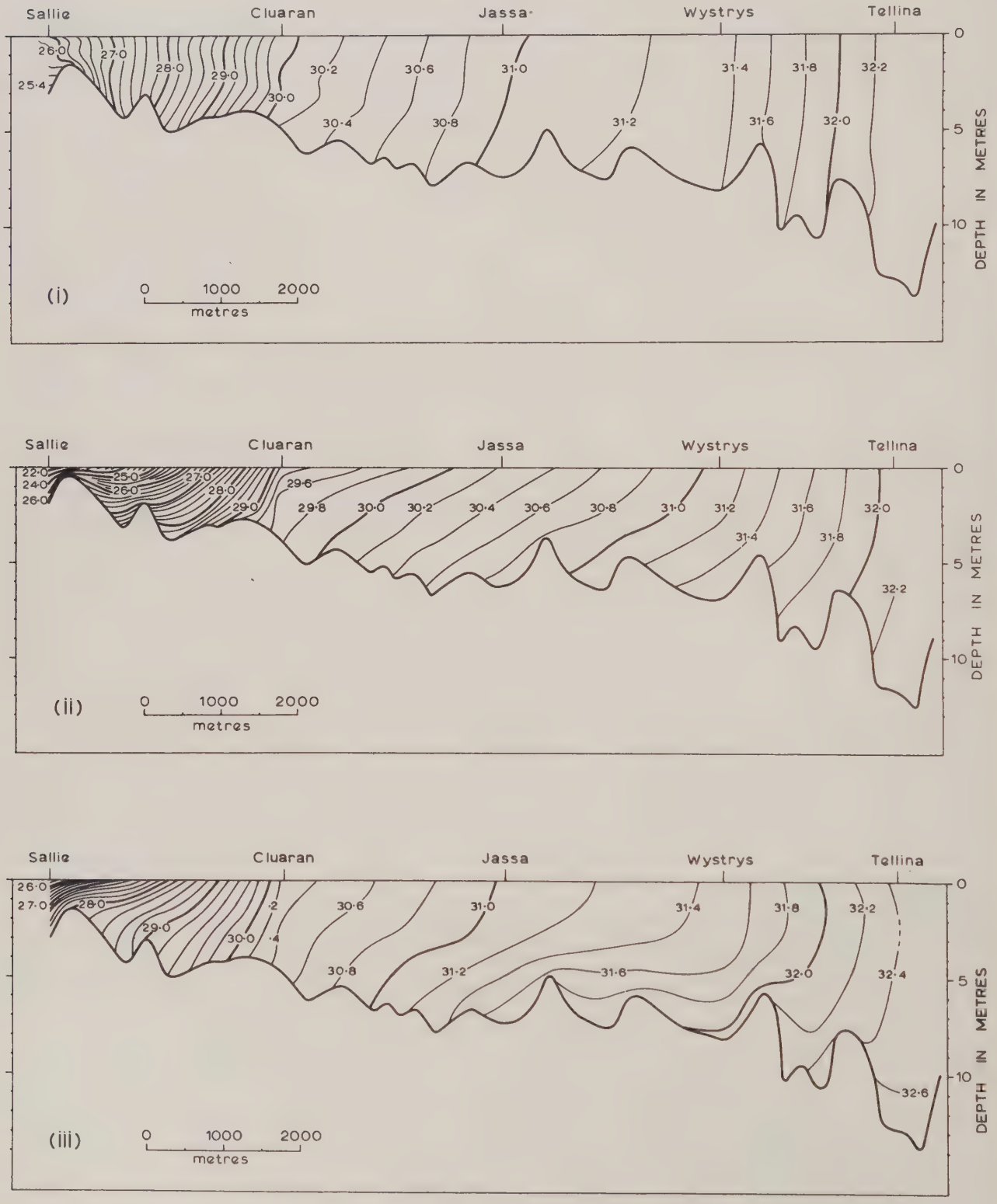


Fig. 6. *Distribution of temperature* (°C) *observed along the length of the estuary during Survey A*1, (i) *at low water*; (ii) *at high water.*

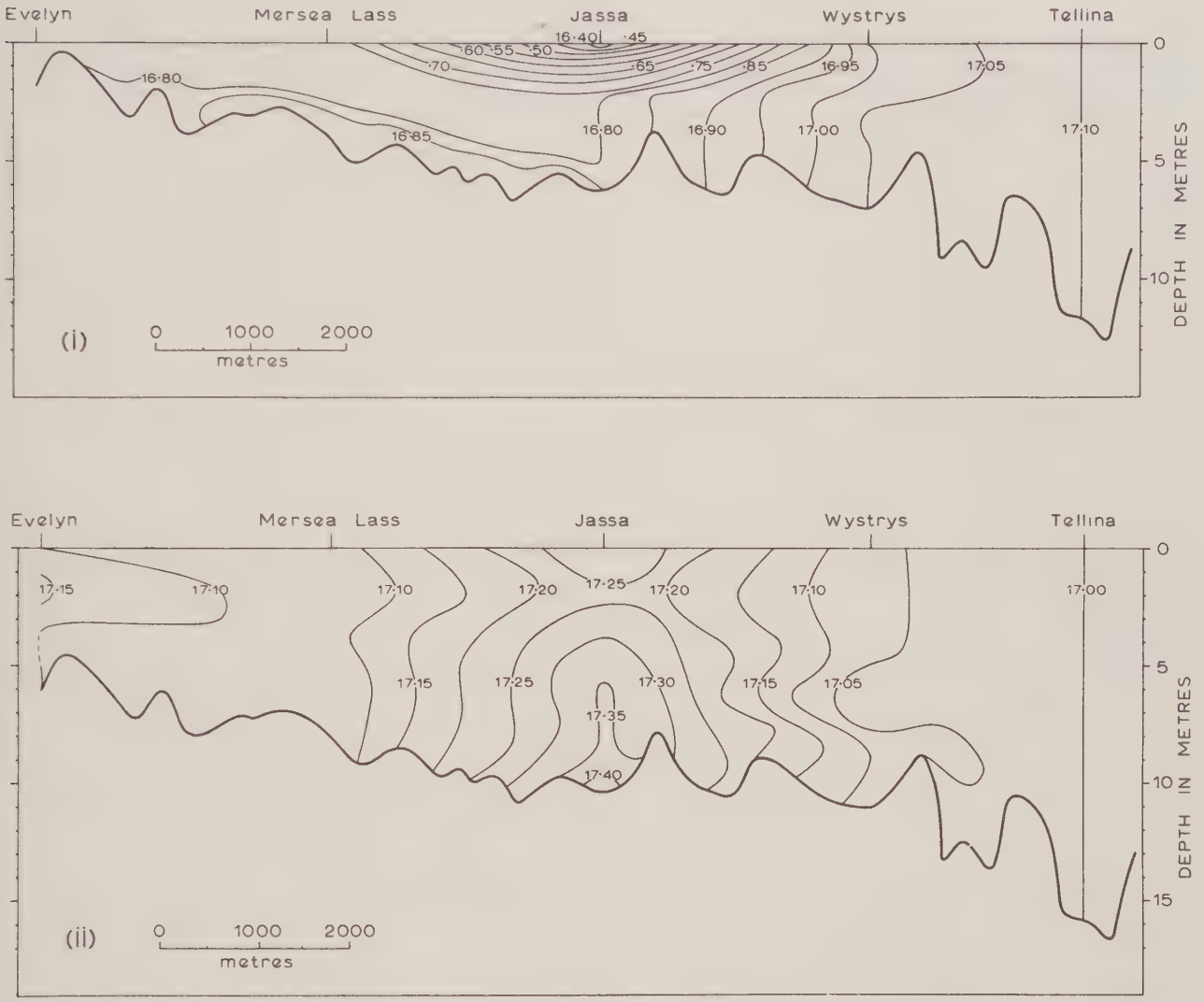


Fig. 7. *Distribution of temperature* (°C) *observed along the length of the estuary during Survey C*1, (i) *at low water*; (ii) *at high water.*

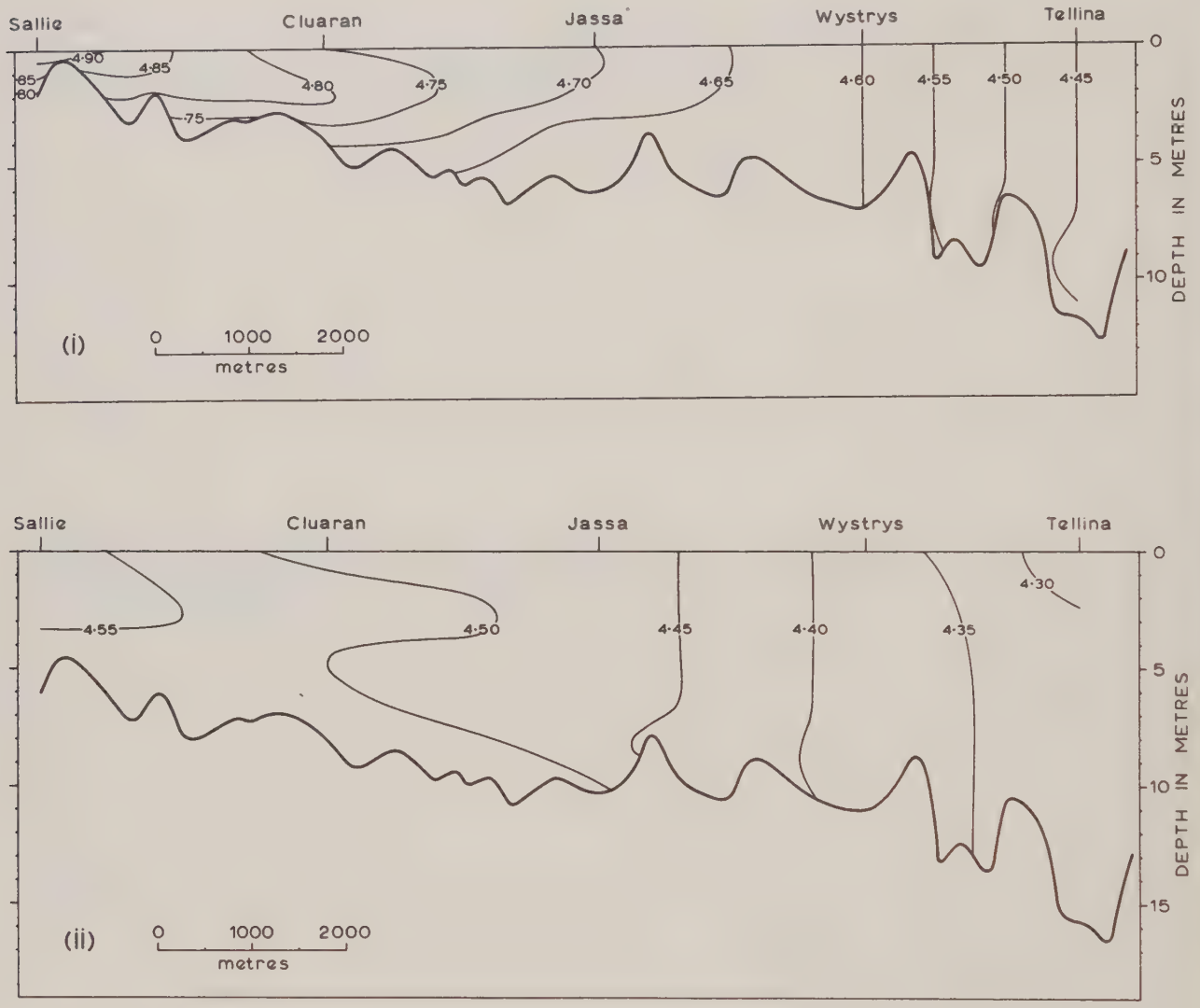
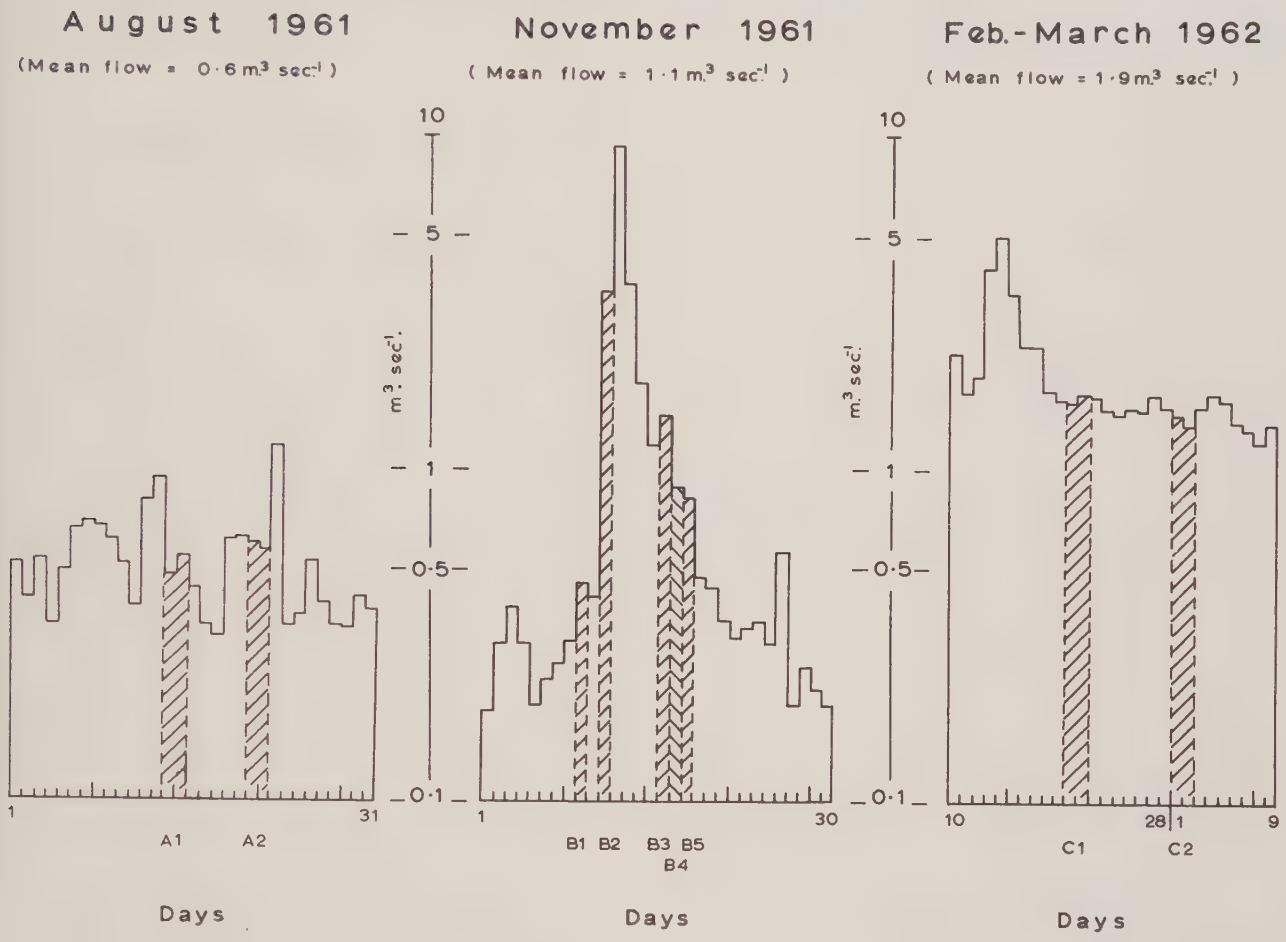


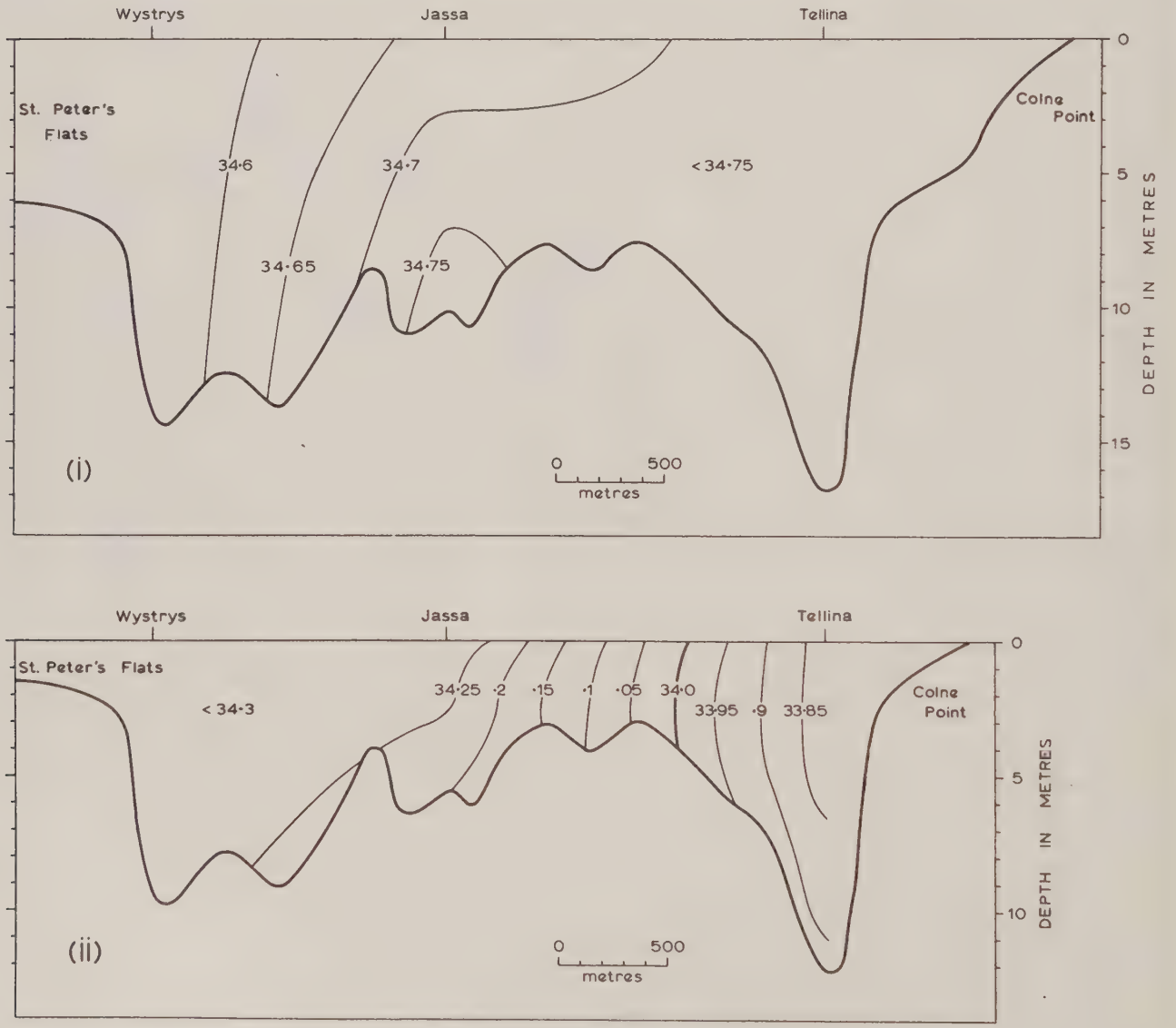
Fig. 8. *Histograms showing freshwater flow into the Blackwater estuary in August and November* 1961 *and February-March* 1962.



LATERAL STRATIFICATION

The information obtained from the November 1961 surveys (B1-B5) had enabled diagrams to be drawn showing the salinity and temperature distribution for high- and low-tide conditions in the five cross sections worked. Some lateral stratification is indicated in all five sections, although only to a small degree near to and just upstream from the power station. These sections will now be discussed briefly, starting with the most seaward one (B1).

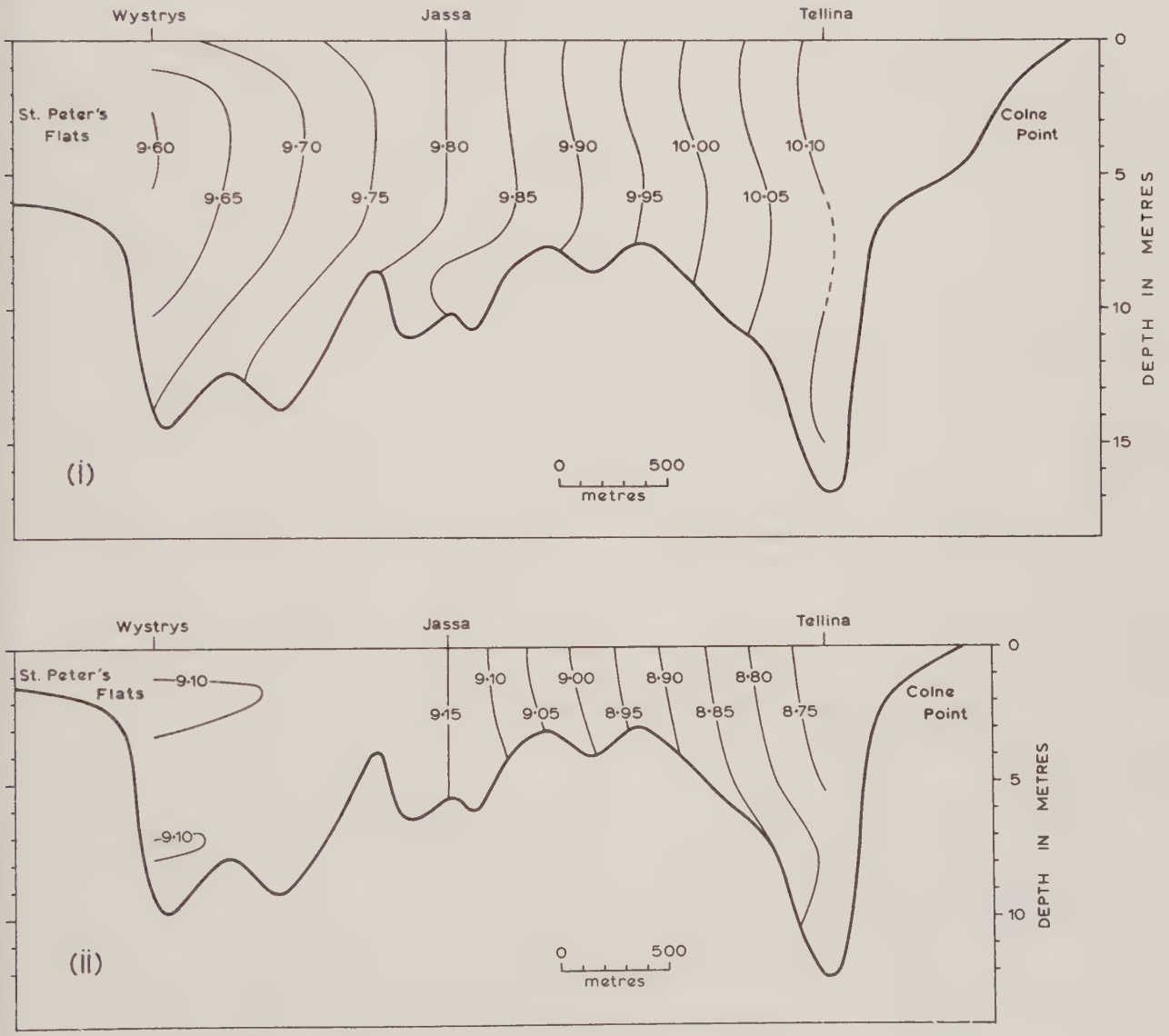
Fig. 9. *Distribution of salinity* ($^0/_{00}$) *across Section B*1, (i) *at high water*; (ii) *at low water.*



(*i*) *Section B*1*: St. Peter's Flats-Colne Point* (*Figures* 9-10)

At high water the higher temperatures and salinities are found towards the northern shore. There seems to be clear evidence here that the low salinity water due to the Blackwater outflow is tending to keep to the southern side of the estuary, as it would do under the influence of Coriolis force. The interpretation of the low-water distributions is not quite so straightforward, but it would seem probable that the discharge from the Colne is responsible for the lower values of temperature and salinity found near the northern side at this time.

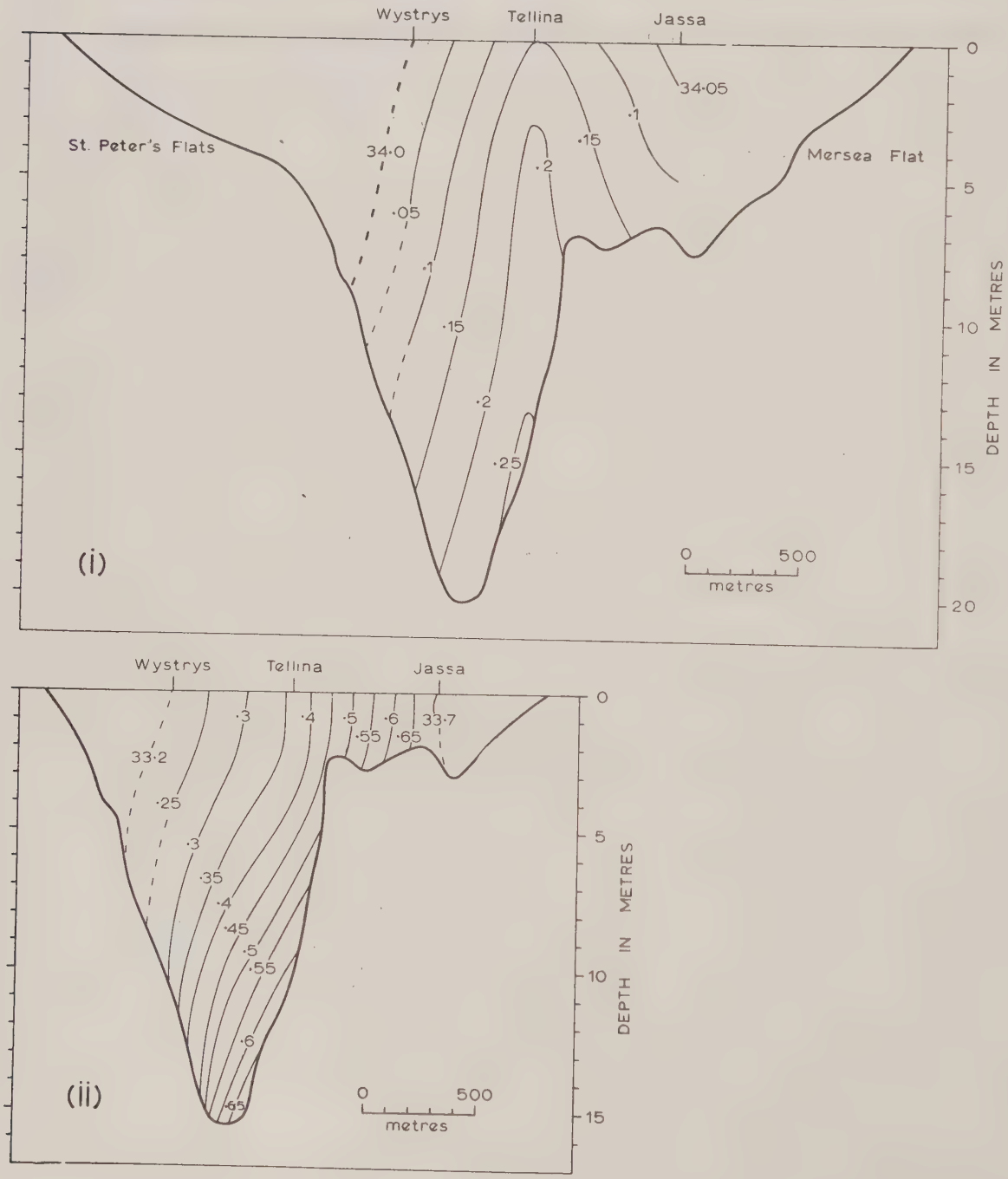
Fig. 10. *Distribution of temperature* (°C) *across Section B*1, (i) *at high water*; (ii) *at low water.*



(ii) Section B3: St. Peter's Flats-Mersea Flat (Figures 11-12)

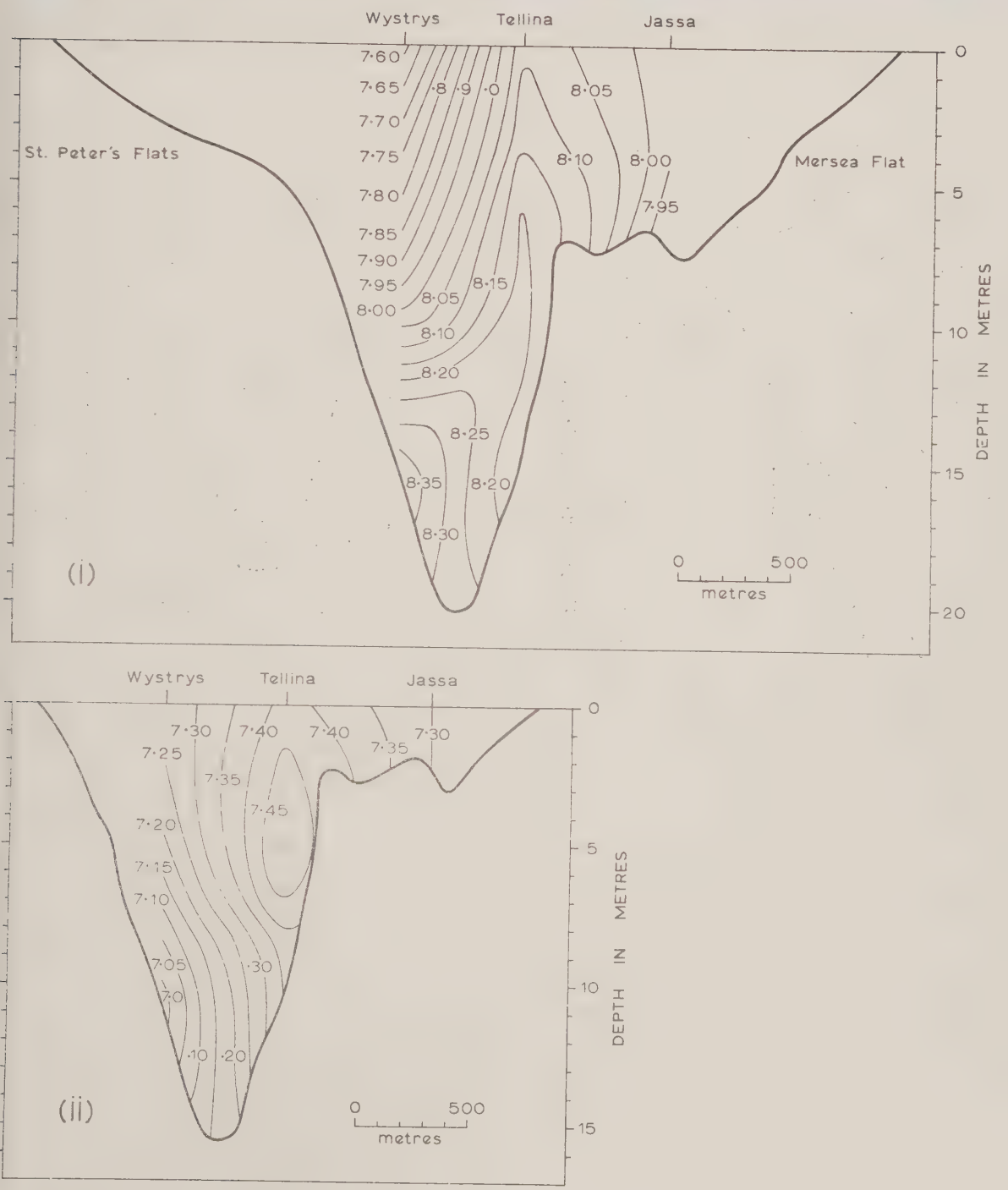
In this section the effect of the discharge from the Colne is apparent at high rather than low water, which is the reverse of the situation discussed for Section B1. The difference would appear to arise because this section is west of the mouth of the Colne whereas Section B1 is just east of it. If we regard the distribution in the northern half of the section as being influenced by the Colne the results for the southern half may be interpreted as indicating the sort of lateral stratification that might otherwise have been expec-

Fig. 11. *Distribution of salinity* (‰) *across Section B3,* (i) *at high water*; (ii) *at low water.*



ted. In this half section the incoming waters appear to tend to keep to the northern side. At low water the situation is simpler, both temperature and salinity increasing toward the northern shore, although the temperature in the vicinity of *JASSA* appears to be a little lower than might have been anticipated. This probably resulted from cooling of the water lying on the flats at the side of the estuary. As for Section B1 we have evidence of lateral stratification, but modified by the effect of discharge from the Colne.

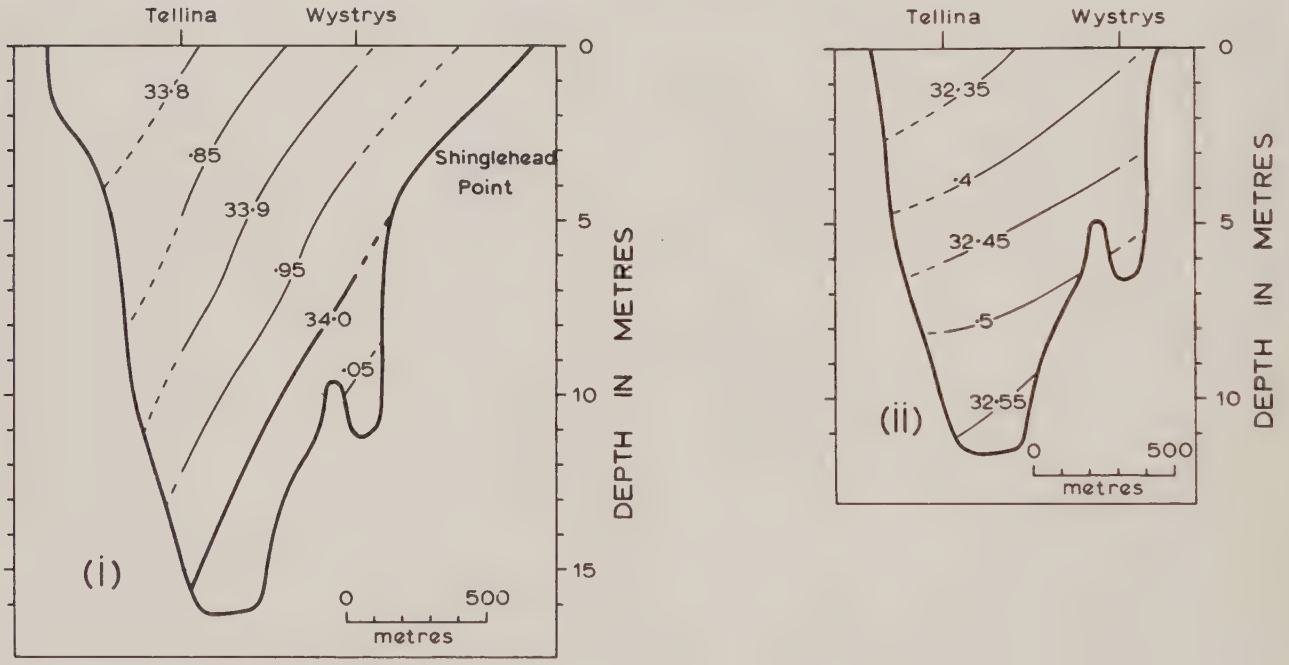
Fig. 12. *Distribution of temperature* (°C) *across Section B*3,(i) *at high water*; (ii) *at low water.*



(*iii*) *Section B5: The Power Station Transect* (*Figures* 13-14)

The interpretation of the results from this section has presented some difficulty. It was most unfortunate that the third vessel, *JASSA*, was unable to work on the day this section was surveyed; because of this, great care is needed in considering the salinity and temperature distributions drawn. Other work carried out on this section in Operations 1 and 2 indicated that in winter the centre of the estuary may be expected to be more saline than the sides, over most of the tidal cycle (Figure 15). It should be mentioned that these preliminary surveys were not intended to provide such accurate information as the later work, but the evidence on this point nevertheless does appear to be reasonably clear. Evidence from this earlier work has been introduced in this context merely to illustrate that the centre of the estuary probably was more saline than the sides under high-water conditions in November 1961, and not with the intention of showing

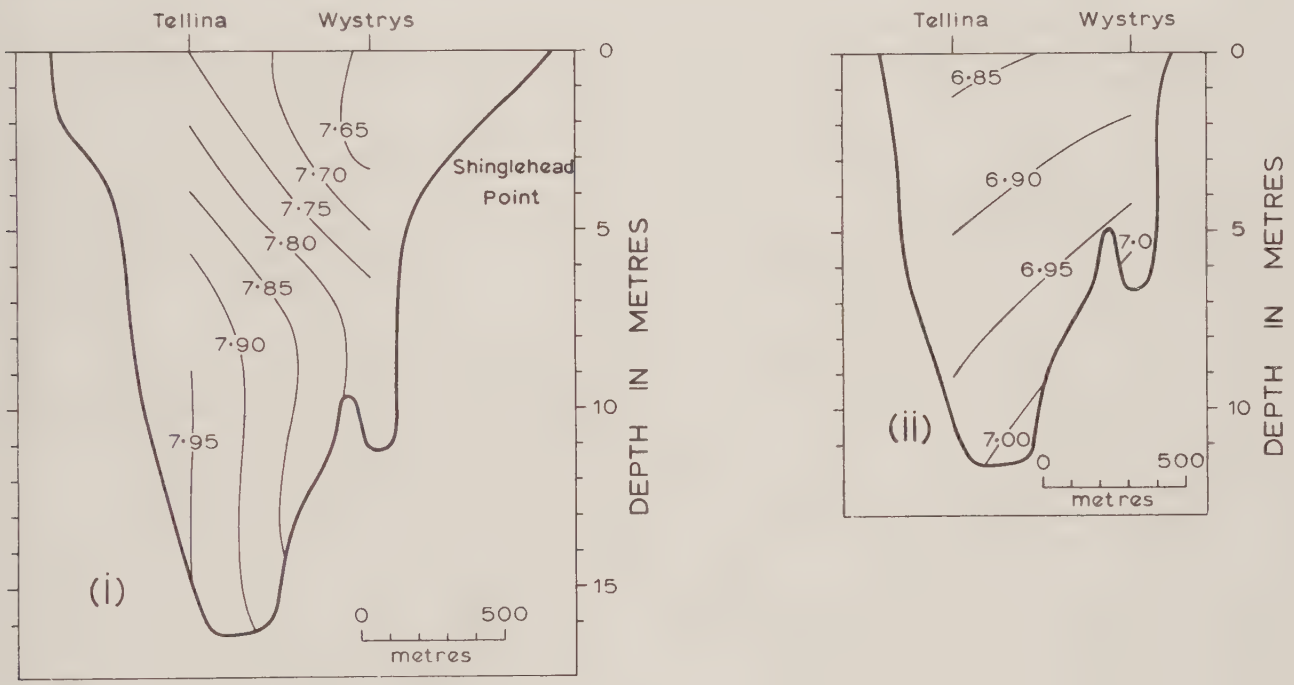
Fig. 13. *Distribution of salinity* ($^0/_{00}$) *across Section B5,* (i) *at high water*; (ii) *at low water.*

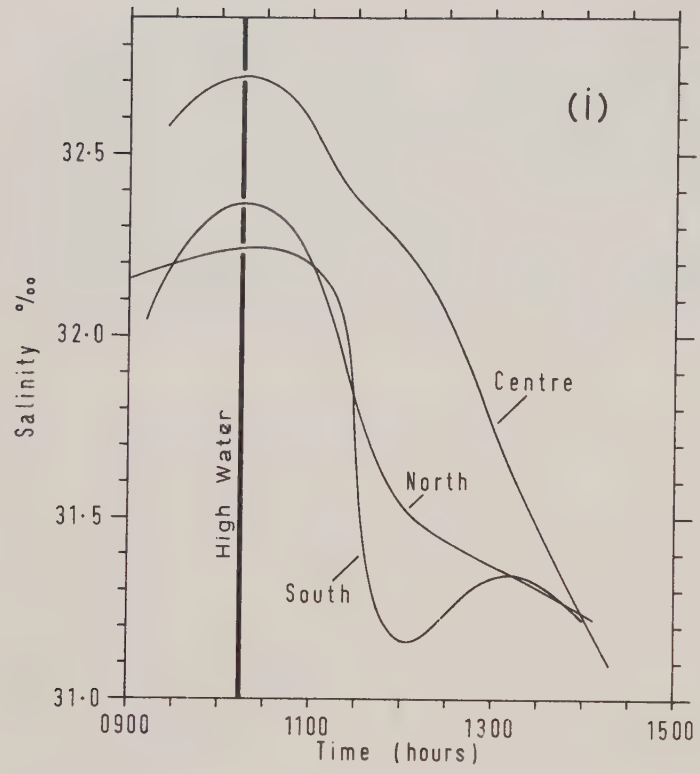


the magnitude of any such salinity difference. Values of surface salinity across this section were also recorded during Survey A3 in August 1961 (Figure 16); although these show the centre of the estuary as being less saline than the sides this does not necessarily contradict the earlier results. It will be shown later that in summer evaporation over the flats bordering the estuary plays a significant role, and this may account for the higher salinities found by *WYSTRYS* and *JASSA* on this occasion.

One feature of the results for this section which was also found for Section B3 is that differences across the estuary are more marked at high water than at low. As in the case of Section B1, this points to an effect of the Colne discharge. On the basis of the evidence available we might expect Section B5 to resemble B3, although it is important to remember that the evidence is less conclusive in the case of Section B5.

Fig. 14. *Distribution of temperature* (°C) *across Section B5,* (i) *at high water*; (ii) *at low water.*




(i)
32·5
32·0
31·5
31·0
Salinity ‰
High Water
Centre
North
South
0900
1100
1300
1500
Time (hours)

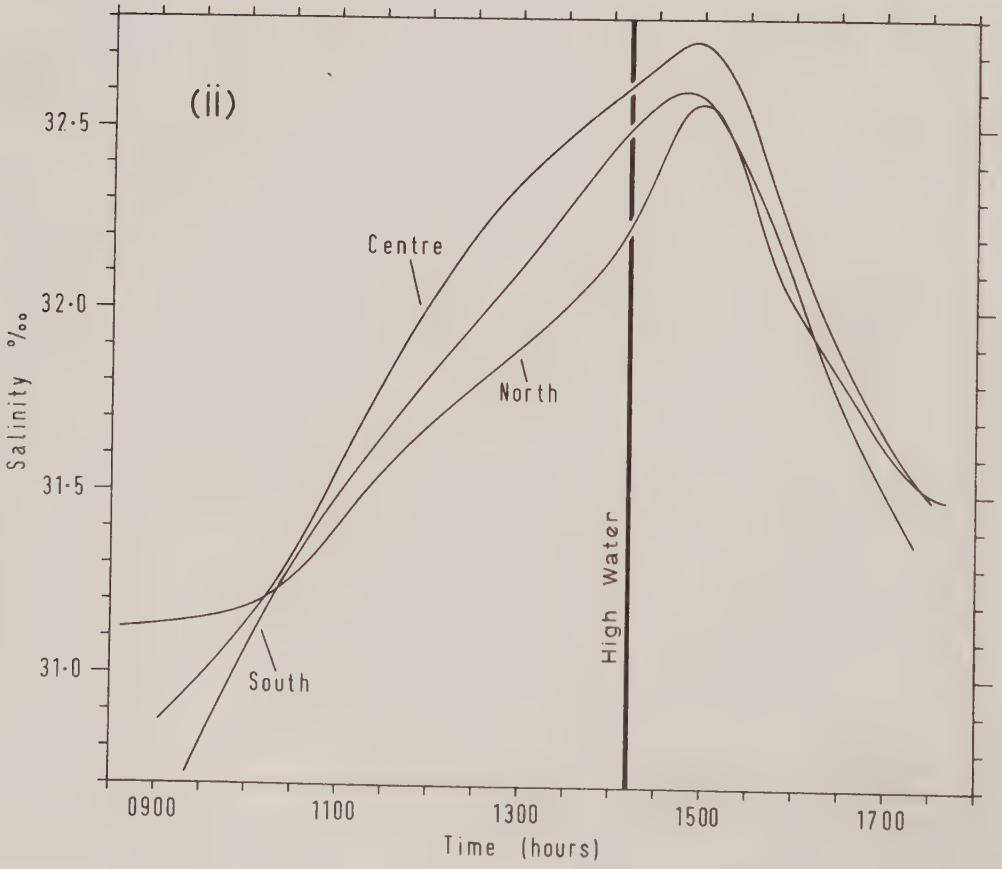
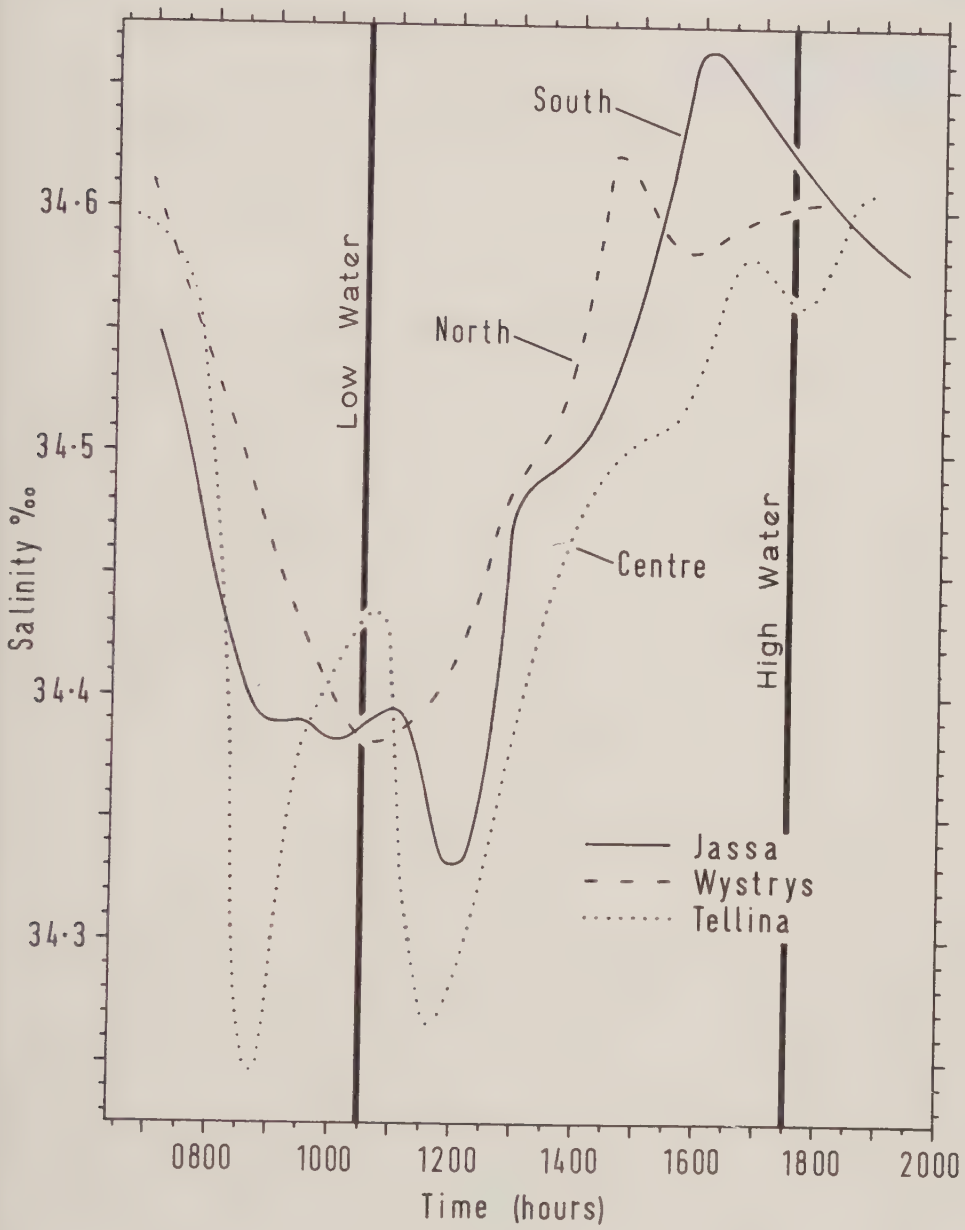

(ii)
32·5
32·0
31·5
31·0
Salinity ‰
Centre
North
South
High Water
0900
1100
1300
1500
1700
Time (hours)

Fig. 15. *Salinity variation across the power station transect during the preliminary surveys:* (i) *Operation* 1; (ii) *Operation* 2. —*see page* 24

Fig. 16. *Salinity variation across the power station transect during Operation* 3, *Survey A*3.



(*iv*) *Section B2: St. Lawrence Creek-Thirslet Creek* (*Figures* 17-18)

The very considerable degree of mixing of the water in this region is well illustrated by the salinity and temperature distributions at high tide. A tendency for fresh water to keep to the southern bank is indicated by the low-tide salinity distribution. The low-tide temperature distribution, indicating a slightly lower temperature on the northern side, may be affected by cooling of the water before it runs off the extensive Thirslet-Goldhanger mud-flat area.

(*v*) *Section B4: Stansgate Abbey-Goldhanger Spit* (*Figures* 19-20)

Results for high tide show this section as differing appreciably from the last. There seems to be a definite tendency for the northern side to be more saline than the south, with the degree of mixing of the water much less than in the St. Lawrence Bay area. The low-tide distributions, particularly in the case of salinity, confirm this picture.

Fig. 17. *Distribution of salinity* ($^0/_{00}$) *across Section B2,* (i) *at high water;* (ii) *at low water.*

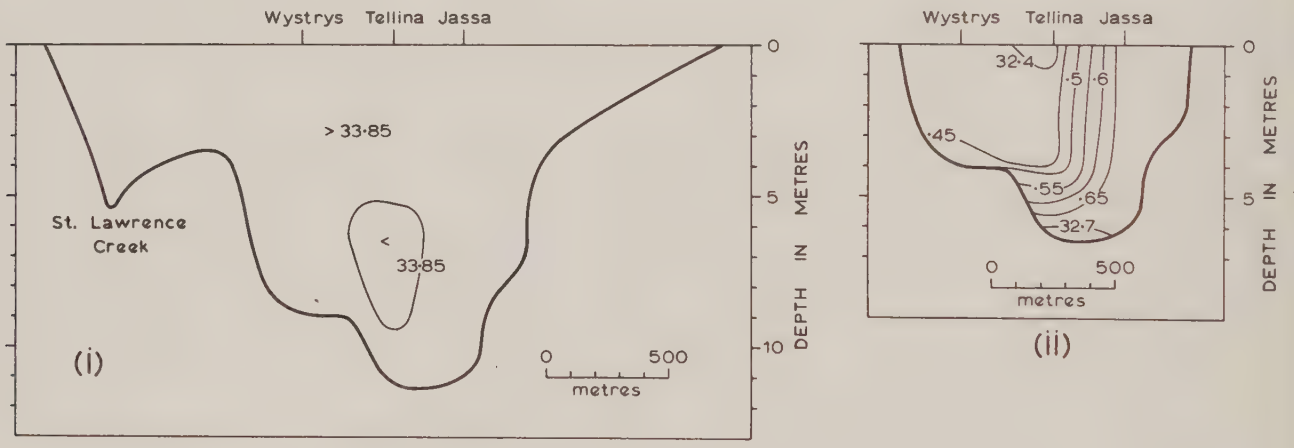
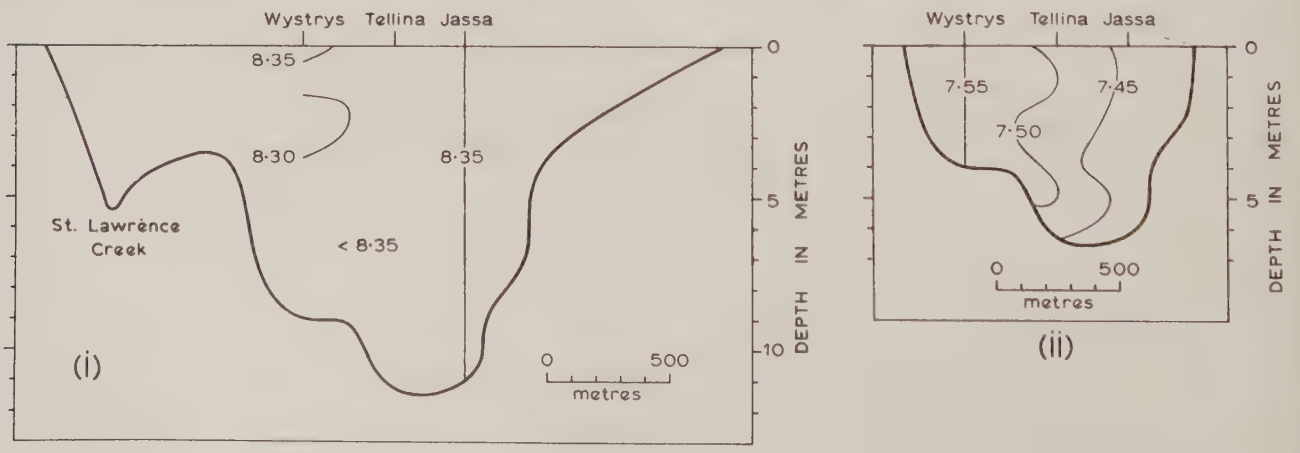


Fig. 18. *Distribution of temperature* (°C) *across Section B2,* (i) *at high water;* (ii) *at low water.*



(*vi*) *Comments on Operation* 4

One difficulty encountered during the November 1961 surveys has already been mentioned, viz. the inability of *JASSA* to work Section B5. A second factor which gives rise to some difficulty when comparing results from these surveys is the abnormally large river flow on 12 November, approximately 109.10^4 m^3. We have already seen, in discussing vertical stratification above, that a river flow in excess of 40.10^4 m^3 per day is likely to cause some vertical stratification towards the head of the estuary. It is unfortunate that such an exceptional peak of river flow should have occurred a little less than one week before Surveys B3, B4 and B5. In view of the results of Survey C1 it would seem probable that at the time of these three surveys there must have been some vertical stratification at the head of the river and there may also have

Fig. 19. *Distribution of salinity* ($^0/_{00}$) *across Section B*4, (i) *at high water*; (ii) *at low water.*

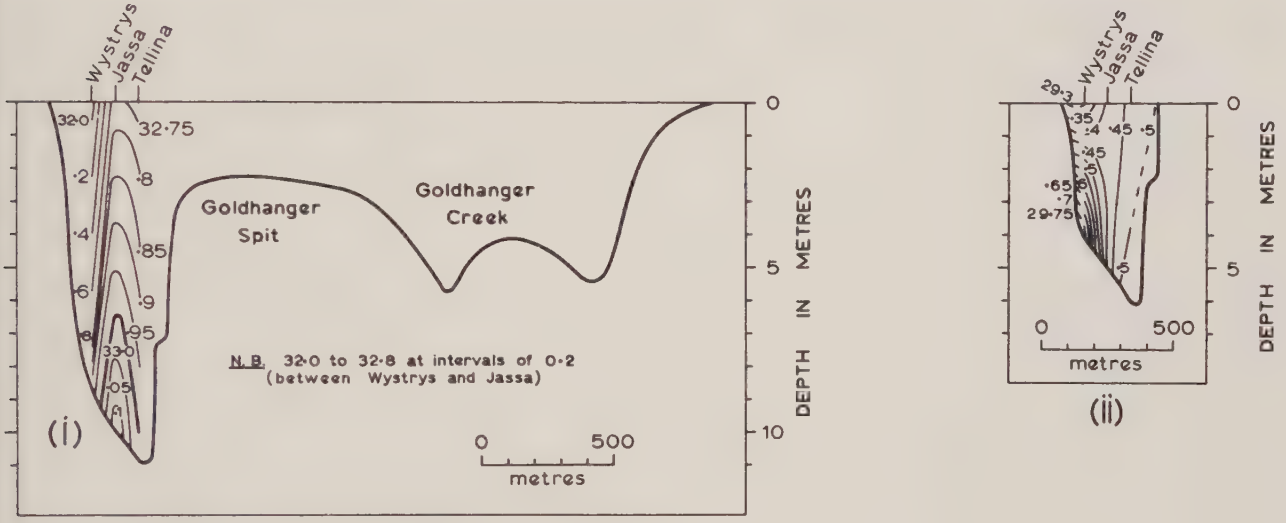
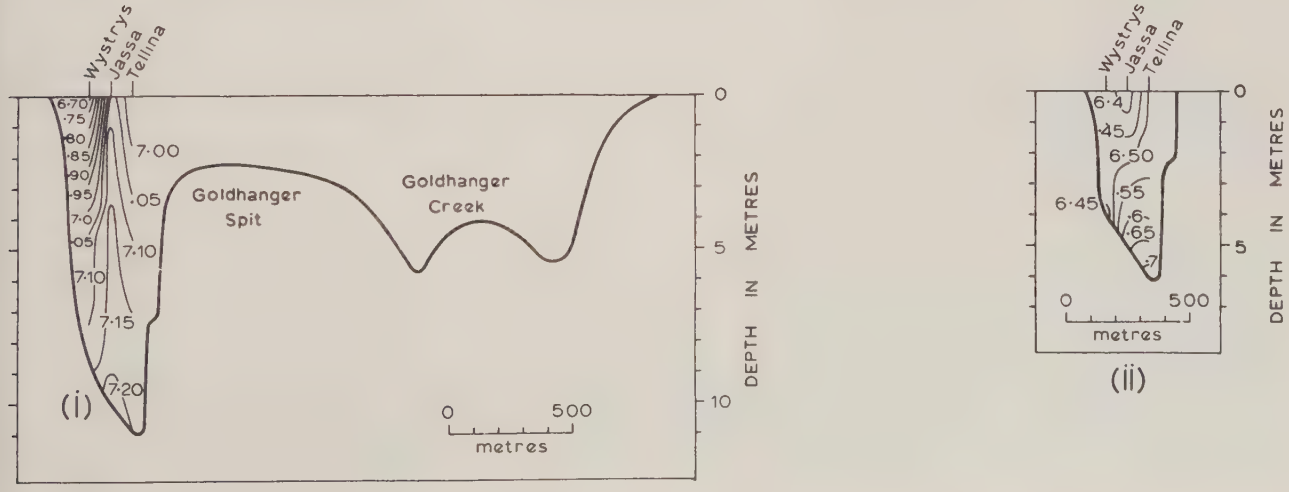


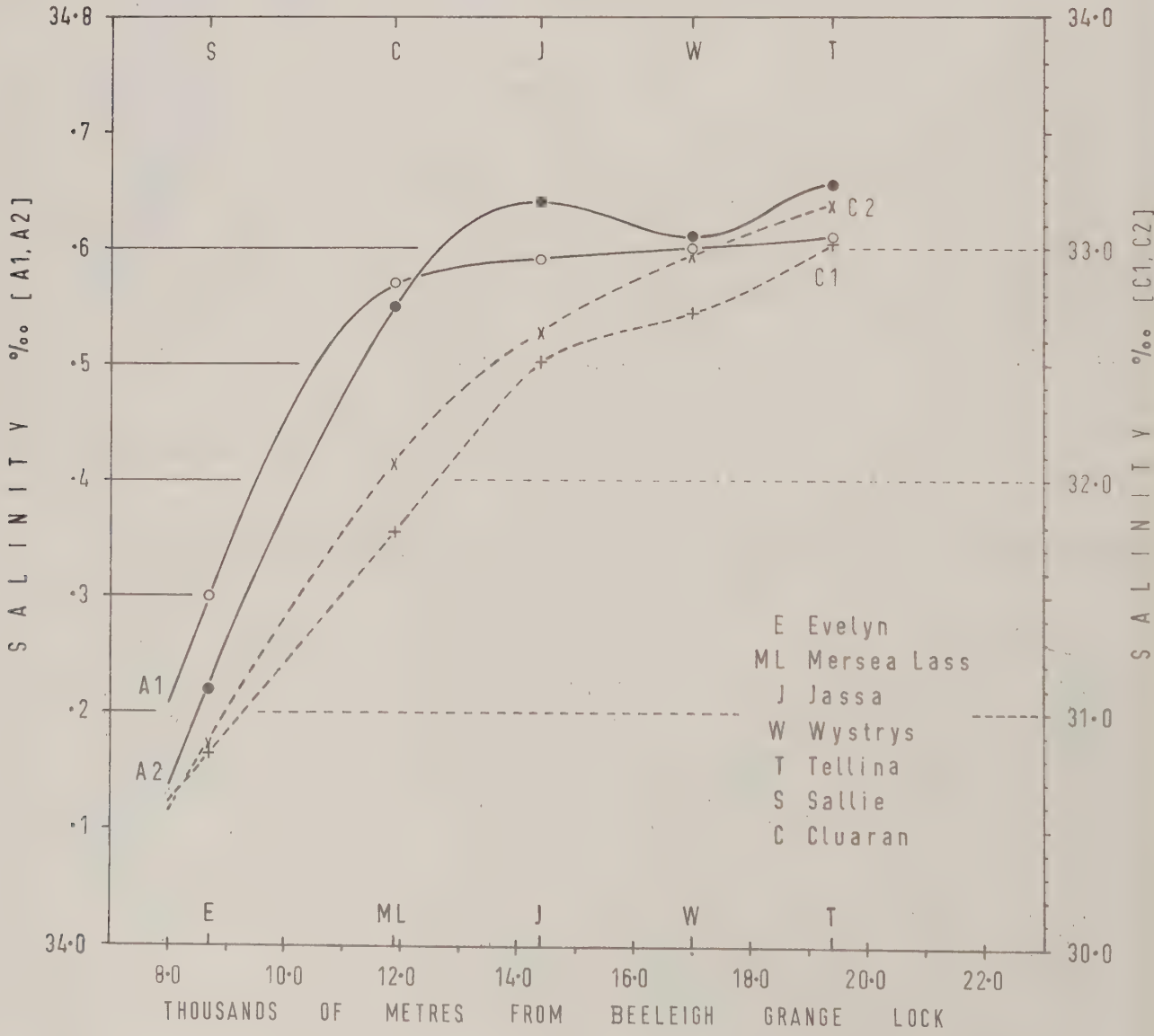
Fig. 20. *Distribution of temperature* (°C) *across Section B*4, (i) *at high water*; (ii) *at low water.*



been effects further downstream. It would appear to be very likely that the salinity gradients observed in Section B4 were partly a consequence of the river flow on 12 November. Whether or not the situation in Section B5 was appreciably affected is difficult to say, but if there were any effect it would have been to produce results indicating greater salinity gradients and stratification of flow than normal. The observed salinity gradients, as we have seen, were quite small and an examination of the current measurements indicated very little stratification of flow indeed.

When allowance is made for the various difficulties of interpretation we are left with the conclusion that the estuary does exhibit some lateral stratification, although this seems to be very slight in the St. Lawrence Bay area and may be slight from this region to the vicinity of the power station.

Fig. 21. *Variation of surface salinity along the length of the estuary at high water.*



COMMENTS ON THE SALINITY DISTRIBUTION OBSERVED IN THE ESTUARY

The results of the salinity measurements have already been referred to extensively in discussing the possibility of stratification. It is now proposed to discuss other features of these results which have not so far been mentioned. The distribution of surface salinity along the length of the estuary (Figure 21), to which reference was made in the Introduction, is quite consistent with the variations of salinity recorded by *TELLINA* when working at position V at the mouth of the estuary during Operations 3, 4 and 5 (Figure 22). To facilitate comparison between the graphs of these results, the times of high and low water have been made to coincide in all of them; this has involved the adoption of a nominal timescale, 0 hours corresponding to low water in all cases. It is clear that the variation of salinity over a tidal cycle in summer is quite different from that observed in spring, the maximum surface salinity in summer being constant to within $\pm 0{\cdot}03^0/_{00}$ for almost six hours, whereas in spring the same variation takes place in approximately one hour. These figures necessarily reflect the distribution of salinity along the length of the channel, the value being almost constant in August but showing appreciable increase towards the sea in March. It is suggested, however, that more is to be deduced from the results than a mere difference in seaward salinity gradient. The results for both August surveys indicated that there is some factor tending to increase the surface salinity which takes effect in the power station region some appreciable time after high tide. Thus the maximum salinity corresponding to the afternoon tide of Survey A1 occurred some two-and-a-half hours after high water (Figures 22 and 23). The curves for the November and February results do not show this effect, so that the cause appears to be related to some seasonal variation. When considering this anomalous variation of the salinity in summer it is instructive to study the salinity difference (ΔS) between surface and bottom. Figure 24 shows how ΔS varied over the two tidal cycles of the A1 survey for positions III, IV and V. It will be seen that for all positions there are times when the surface salinity is significantly greater than that at the bottom; this unexpected occurrence will be referred to as a negative salinity difference. These anomalous occurrences can be explained neither by temperature differences, nor as the result of the action of surface wind. What is happening is that a dense saline layer of water is spreading across the surface. It is assumed that this saline surface 'skin' spreading seawards on the ebb tide has been produced as a result of evaporation, particularly over the mud flat areas. It seems possible that the peak salinity recorded in Survey A1 and mentioned above might well correspond to the arrival at station V of water from the extensive flats of the Goldhanger-Thirslet Creek areas.

The information contained in Figures 22 and 23 was thought to be conveyed most clearly by using a nominal timescale as the X axis. In the case of Figure 24 the actual times of the observations are relevant and the horizontal axis has been labelled accordingly. In order to facilitate comparison between Figures 23 and 24 the high waters in the former have been labelled 'day' and 'night'. Thus the afternoon high water of Survey A1 discussed above occurred at 1500 hours and the peak of surface salinity at approximately 1700 hours. This peak of surface salinity is seen to have corresponded to a minimum value of ΔS ($-0{\cdot}012^0/_{00}$). The high-salinity water recorded at this time was thus at the surface, which confirms the suggestion that it came from the flats bordering the estuary. It may be significant that this situation did not recur on the night tide, when evaporation over the flats should have been less important; in fact a little light rain was recorded during the night flood tide.

Evaporation over the mud flats in summer is also indicated by the salinity results across the power station transect, which have already been discussed (Figure 16). The indication here was that in summer higher-salinity water is associated with the sides of the estuary. This is the converse of the situation often found in tidal flat estuaries, where the higher-salinity water is found in the main channel and particularly so about the time of high water (Postma 1954). This process is associated with a turning of the tide earlier at the sides of an estuary than at the centre, which can produce a mixing of lower-salinity water from the flats with more saline water in the main channel as the tide begins to ebb. Table 4 shows the times at which

Fig. 22. *Variation with time of surface salinity at the mouth of the estuary. The variation has been computed relative to the mean* (S_r) *of the extreme values for the survey in question.*

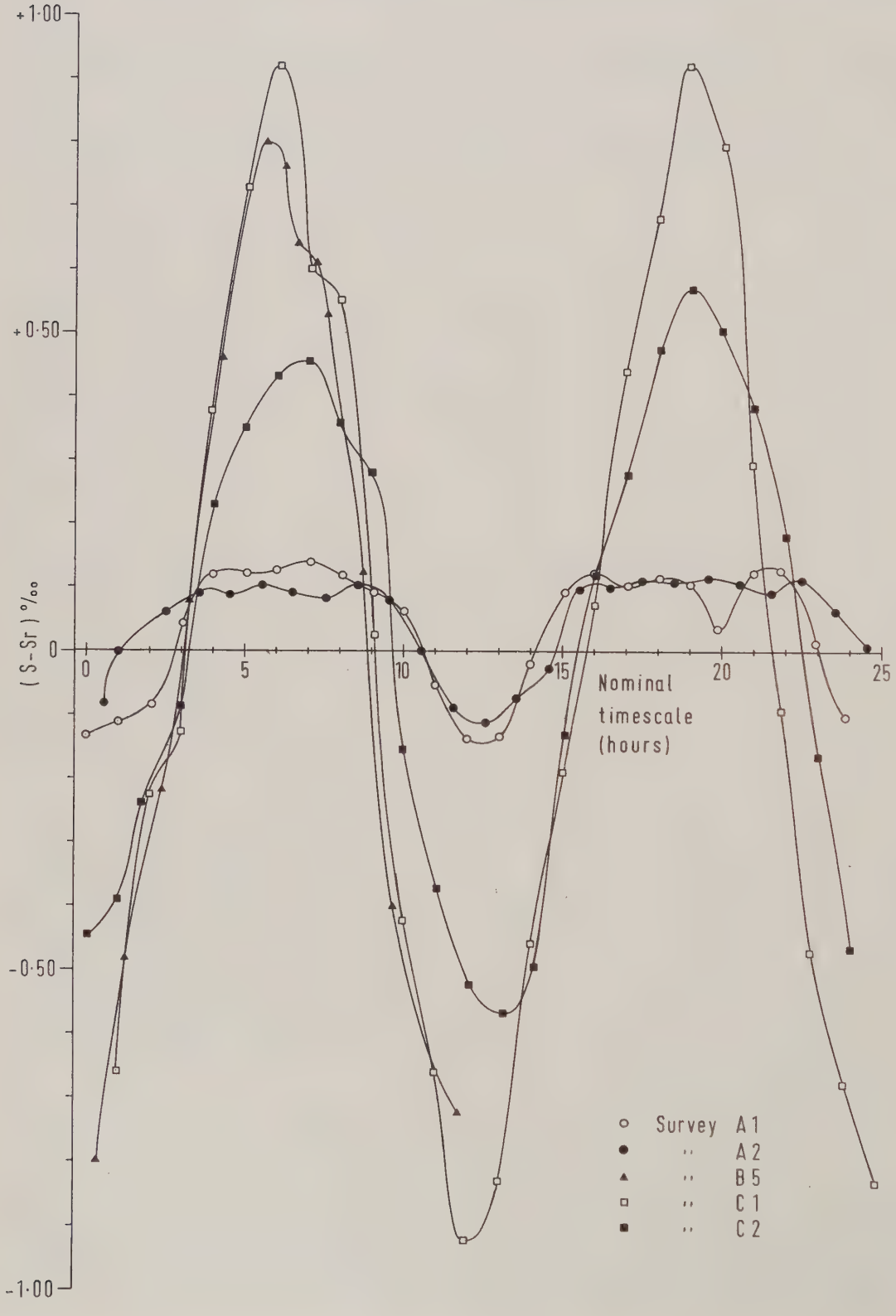
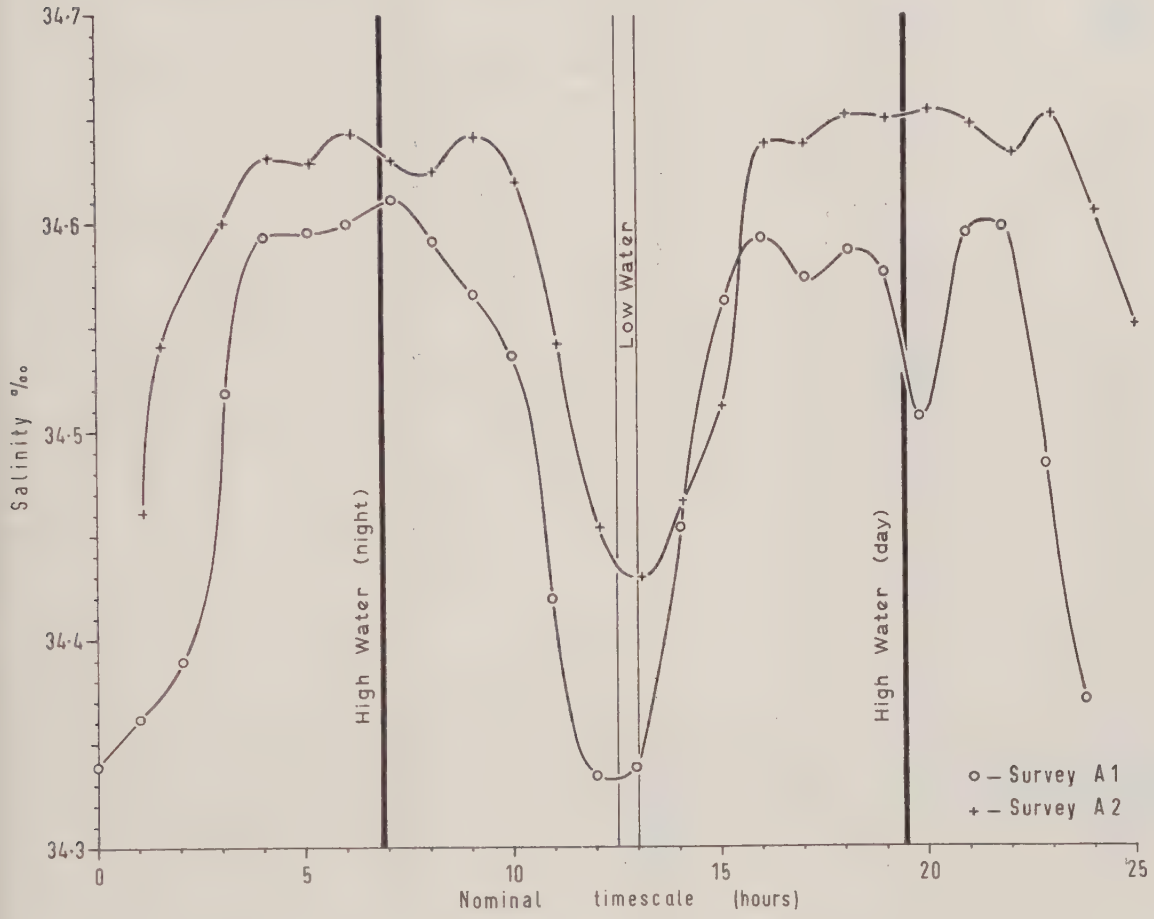


Fig. 23. *Variation with time of surface salinity at the mouth of the estuary (Operation 3, Surveys A1 and A2).*



the tide was observed to turn at the various stations of Operation 4. Although this process can contribute considerably to the degree of longitudinal mixing in an estuary, the results quoted do not suggest that it is particularly important in the Blackwater. It is local knowledge however that the effect does take place, as indeed is to be expected, but it would seem to be confined to relatively small water masses at the sides of the main channel and we must look for other factors in order to explain the high degree of longitudinal mixing that is observed in this estuary.

Additional evidence that high-salinity water is produced as a result of evaporation over the flats is provided by readings taken by C.E.G.B., some of them whilst Survey A1 was in progress. The results obtained, corresponding to approximately low-tide conditions, indicate values of salinity significantly greater than those obtained even at high tide in the mid part of the estuary:

Salinity readings obtained by C.E.G.B. on 15 August 1961

Tollesbury Fleet North Channel	Salcott Creek	Mersea Quarters
0840 hours 34·81‰	0858 hours 34·76‰	0853 hours 34·71‰

Fig. 24. *Variation of surface-bottom salinity difference* (ΔS), (*Operation* 3, *Survey A*1).

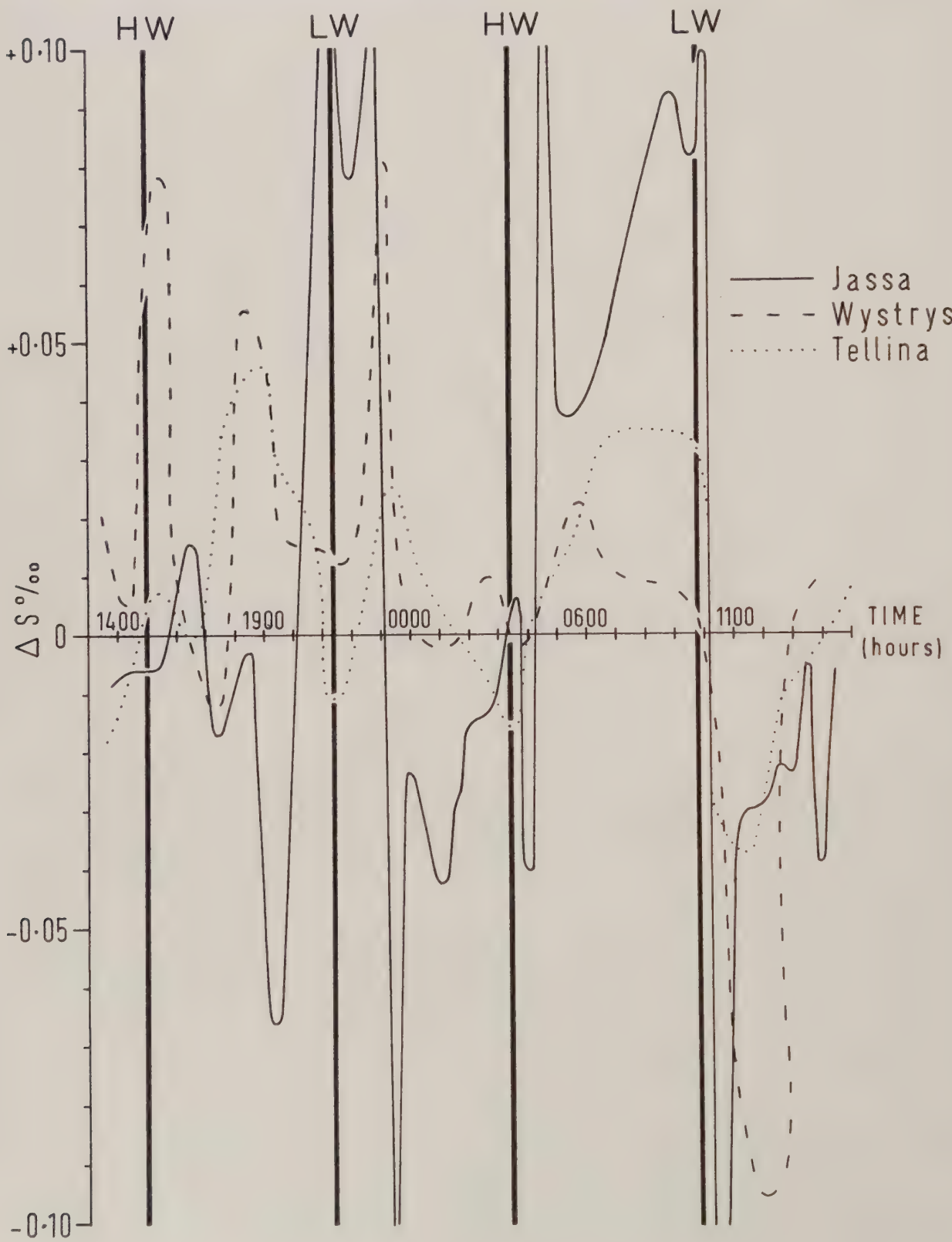


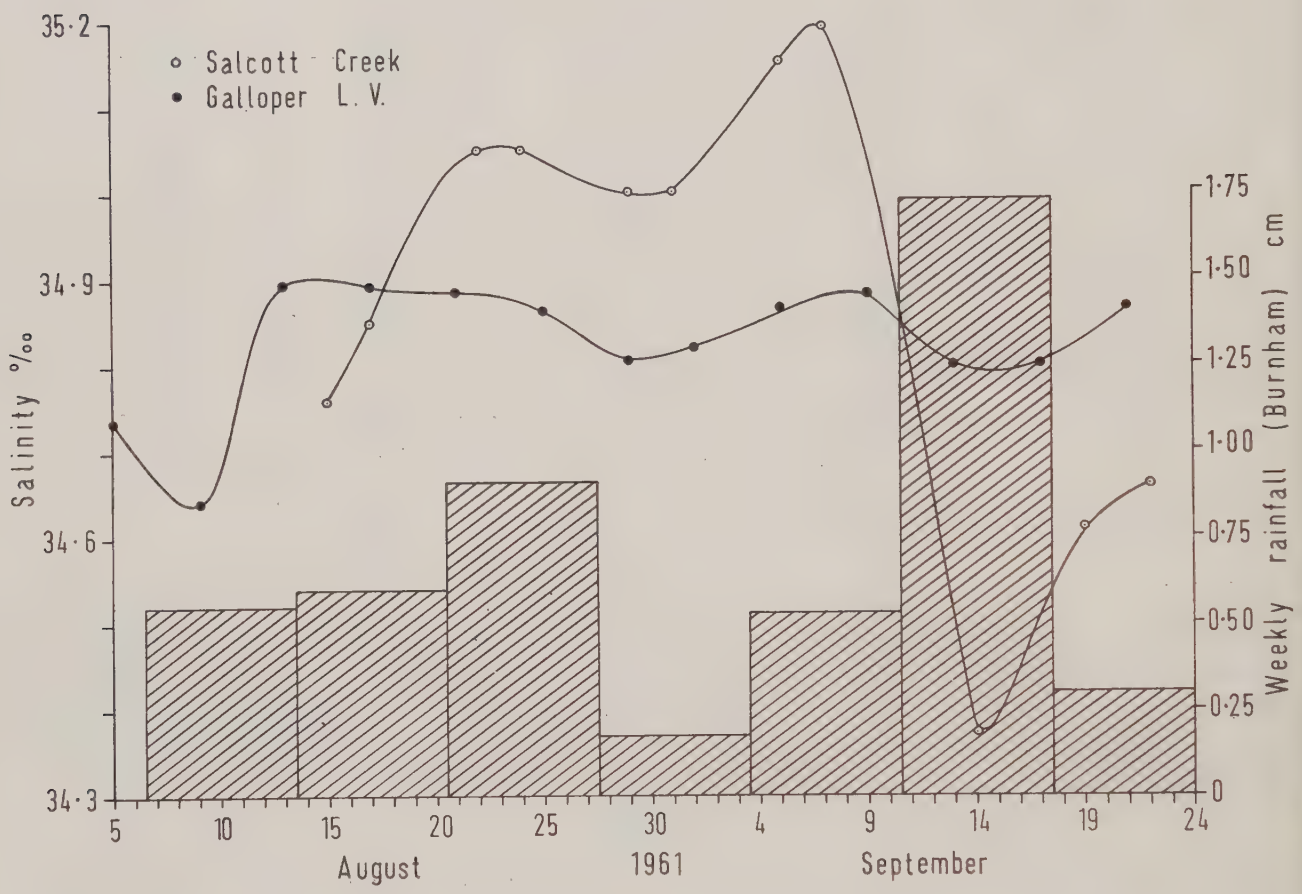
Table 4. *Times of slack water at the various stations (see Figure 2) investigated during Operation 4.*

		TELLINA	*WYSTRYS*	*JASSA*
Survey B1	High water	1224	1224	1241
	Low water	1845	1858	1810
Survey B2	Low water	0810		
	High water	1404	1409	1406
	Low water	2051	2024	2030
Survey B3	Low water	1117	1204	1110
	High water	1837	1809	1816
Survey B4	Low water	1330	1254	1258
	High water	2003	2008	2014
Survey B5	High water	0806	0815	
	Low water	1346	1430	

Figure 25 shows how the low-tide salinity varied in one of these positions over the months of August and September, and for comparison the corresponding variation at the Galloper Lightvessel. A relationship between salinity in the estuary and rainfall has been noticed by Spencer (1965) and this is confirmed by the rainfall figures for Burnham-on-Crouch which have been included in Figure 25 in histogram form. The relationship between rainfall and salinity variation will be pursued further when discussing the estimation of exchange of water between estuary and sea using the freshwater budget.

Although it appears reasonable to explain negative values of ΔS occurring during summer ebb tides as resulting from evaporation over the mud flats, some further explanation must be sought for the negative ΔS values recorded at several stations during a flood tide. Figure 24 illustrates some such instances. It is considered that, once again, the mud flats play a major part. A few measurements have been made of salinity values for small pools of water stranded on the flats at low tide; in summer these frequently exceed sea values by an appreciable amount (A. R. Folkard pers. comm.) This is really only an extension of the action referred to during the ebb, but this time it involves water which is stranded on the flats. It is suggested that the high-salinity water found on the flats at low tide might produce two effects: it might either be absorbed into the mud, whose salt content would in this case increase progressively during the summer months, or it might be swept off by the next flood tide. In this latter case the overall effect upstream of a mud flat area at some time in the period of flood would be similar to that already met with downstream of the flats during the ebb. This situation is suggested by results from *JASSA* and *WYSTRYS* in Survey B2 (Figure 26); *JASSA* was positioned close to but downstream from the Goldhanger-Thirslet Creek mud flat area, whilst *WYSTRYS* near the southern shore had an appreciable mud flat area downstream, the Bradwell Creek area. It may be significant that *WYSTRYS* recorded a negative salinity difference soon after low water and at a time when the water was flowing past her from the direction of the flats (Figure 27 (i)). Other examples of saline water from the flats flowing over less saline water are provided by the summer and winter longitudinal surveys (Figures 3 (vi), 4 (vi) and 5 (i)). In each case we find a negative salinity difference near the head of the estuary as low water approaches (four hours after high water).

Fig. 25. *Variation of salinity at about low tide in Salcott Creek in comparison with that at the Galloper Lightvessel.*



The occurrence of saline surface water over less saline water is quite frequent in the Blackwater, and *JASSA's* results in Survey B2 (Figure 26) illustrate another example of this. At *JASSA's* station, however, the difference occurred at about high water, having built up as water flowed on to the flats. The explanation for this would appear to be in the hydrodynamics of the water flow, and for an explanation we may consider Figure 28. This shows a shore, fairly steeply sloping, but with a wide ledge a little below the high-water mark. The ledge corresponds to the mud flats and the steeper slope to the edge of the main river channel. If we consider the action of an incoming tide on such a shore two possible situations are apparent. In the first case, where the tidal currents are fairly small, we would expect isohalines sloping as shown in Figure 28 (i), so that water from region A would gradually be pushed by advective forces on to the area of the mud flats. As the velocity of the tide increases, current component x would become increasingly less favourable compared with current component y. This might be expected to result from the effect of bottom friction, itself proportional to the square of the velocity, and also because at higher velocities we would expect hydrodynamical effects based upon the energy of the moving water to become more important than water movement resulting from advective forces (Appendix I). Thus, for high values of tidal currents we arrive at the situation in Figure 28 (ii). Again we have a layer of denser and more saline water moving over less dense water, although in this case the latter might be expected to constitute a relatively small pocket.

Fig. 26. *Variation of surface-bottom salinity difference* (ΔS) *recorded close to the sides of the estuary* (*Operation* 4, *Survey B*2).

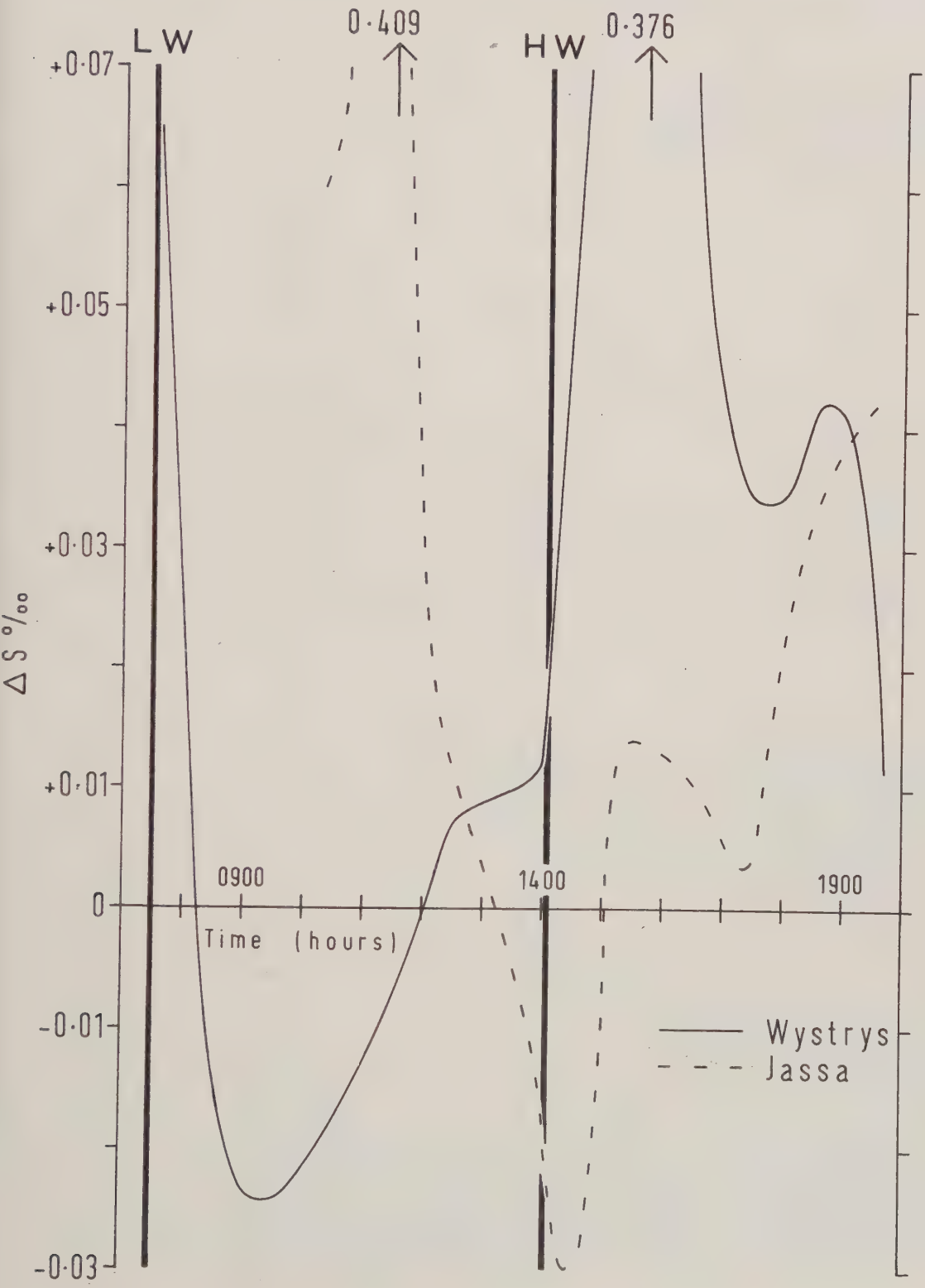


Fig. 27. *Variation of water velocity near the surface and the bottom of the estuary during Operation 4, Survey B2. The vectors have been numbered to indicate the time (in hours) after low-water slack, and in all cases their direction is away from the origin.*
(i) *At a position close to the southern shore;* (ii) *At a position close to the northern shore.*

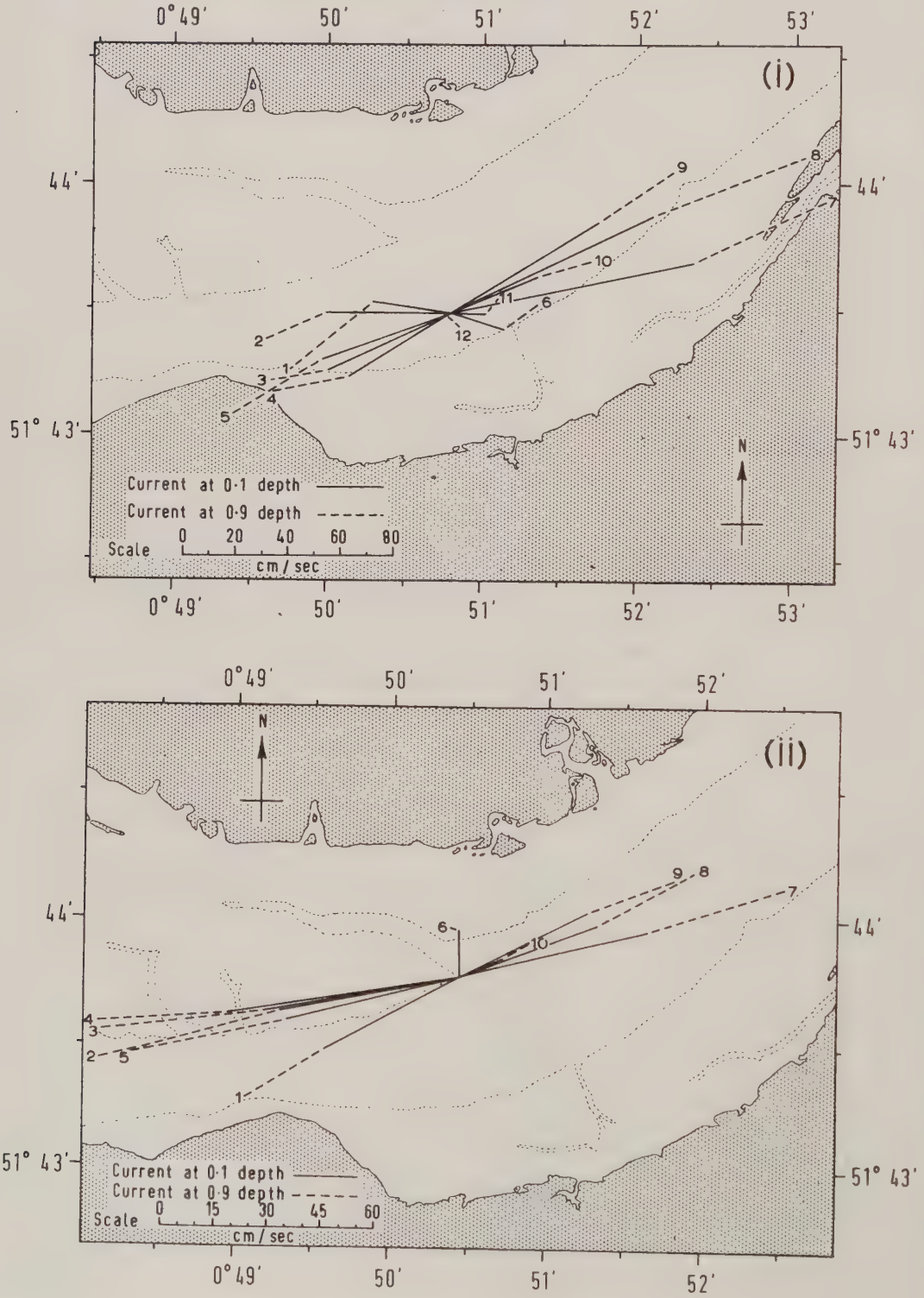
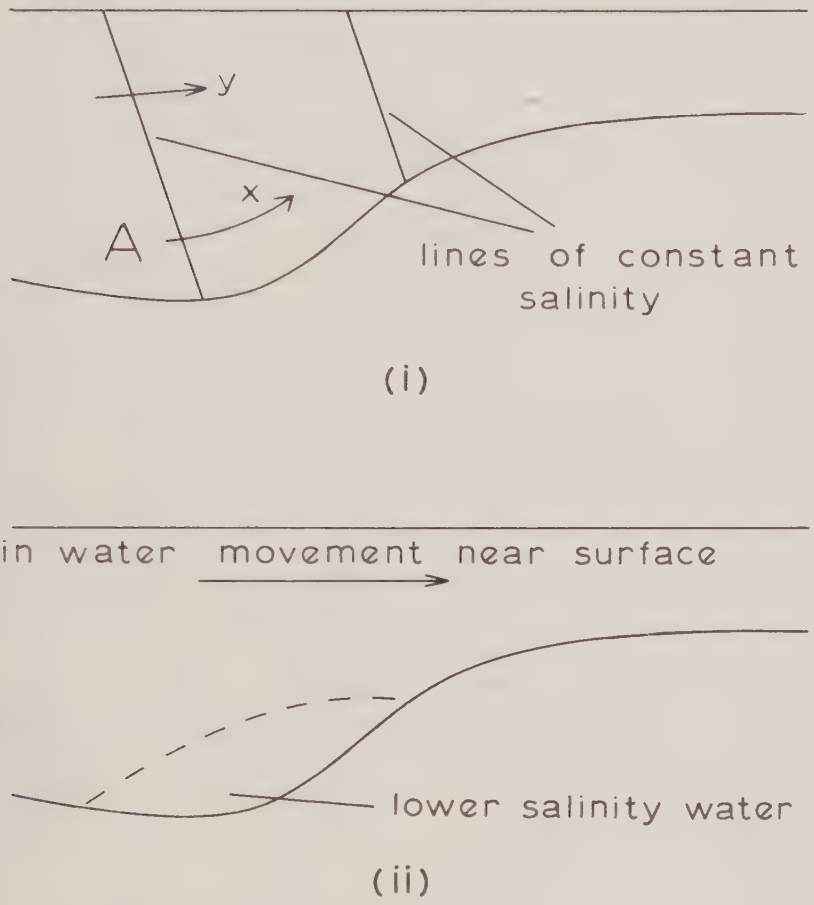


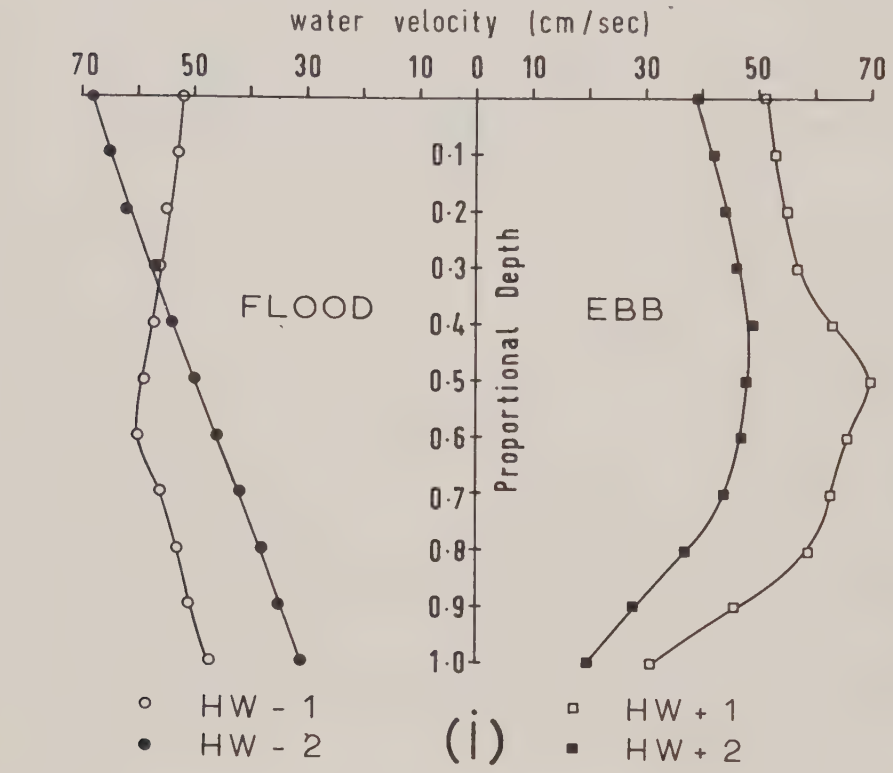
Fig. 28. *Flow of water on to a region of mud flats,* (i) *for low rates of flow*; (ii) *for high rates of flow.*

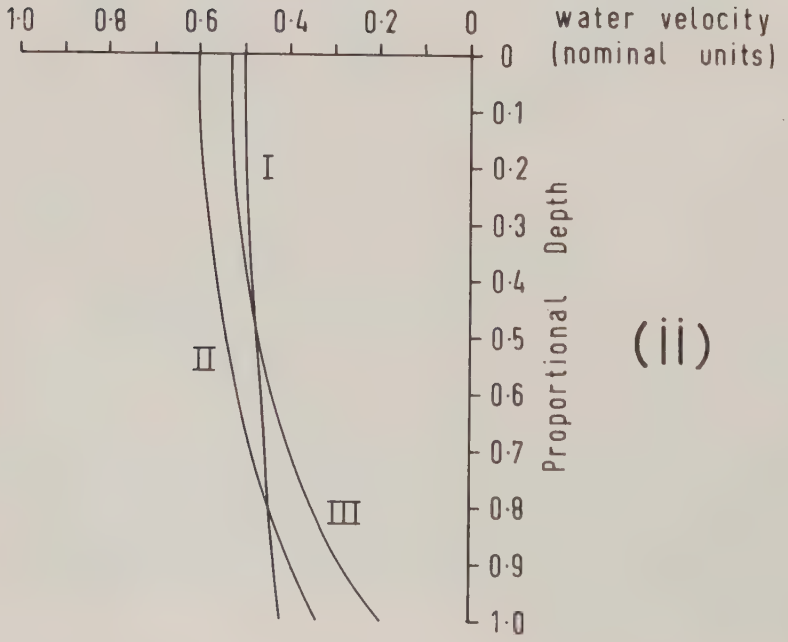


In Figure 29 we show the variation of the magnitude of the current with depth that was recorded by *JASSA* in Survey B2, together with the current depth variation that is predicted by hydrodynamics. A summary of the theory upon which these curves are based is given in Appendix I.

The attempt to calculate the pattern of flow in the vicinity of the mud flats necessarily involves a number of simplifying assumptions, but the theory does agree with the results of observations in predicting a decrease of velocity with depth. This contrasts with the situation found in many coastal plain type estuaries where the greatest velocity during the period of the flood tide is found nearer the bottom than the surface. The current measurements at JASSA during Survey B2 (Figure 27(ii)) provide a further indication that it is the flow of water on to the flats which gives rise to the comparatively large water velocities that are observed towards the surface. It will be seen from Figure 27(ii) that during the first part of the flood the current flows along the main channel, as is to be expected. However, for the majority of the period of flood the current vectors for both surface and bottom point across the mud flats, the surface current being always the greater. It is this tendency for more saline incoming water to flow over less saline water inside the estuary, itself a result of the hydrodynamics of the flow over the bottom topography, which produces a tendency for a vertical negative salinity gradient to be produced during the flood tide. A similar effect has been observed in the Ems Estuary by Dorrestein (1960) who comments on the velocity-depth relation in the mouth of the Dollart. In this case we again find flood water sweeping on to an extensive mud-flat area, although in the Dollart the depth salinity gradient was merely reduced to a small value, it did not reverse as observed in the Blackwater.

Fig. 29. *Depth variation of water velocity;* (i) *Variation recorded close to the northern shore of the estuary* (*Operation* 4, *Survey B*2) *at times within two hours of high water;* (ii) *Variation predicted by hydrodynamics for three positions in the vicinity of a shelving bottom.*





THE VARIATION OF SURFACE SALINITY OVER THE ESTUARY (FIGURES 30 TO 37)

The information for these diagrams should ideally have been obtained at several stations, at various points in the estuary, worked simultaneously. Thus if the 15 stations of Surveys B could all have been worked at the same time the diagrams could have been drawn with some confidence. In fact, as already described, it was necessary to spread this work over several days from 9 to 18 November. It was particularly unfortunate that an exceptionally large river flow occurred on 12 November (Figure 8) and this must have had some effect on the results of the last three surveys. The difficulty in drawing the diagrams is therefore clear, but the attempt was nevertheless considered worthwhile. It was necessary to make some allowance for the effect of the large river flow on 12 November and for the fact that as a consequence all readings from Surveys B3, 4 and 5 might be expected tobe low compared with those of B 1 and 2. It was therefore assumed that the overall variation of surface salinity along the length of the estuary at high water in November was similar to that in March (Survey C1). Figure 22 gives some justification for this but the assumption must involve some loss of accuracy, particularly when an attempt is made to deduce conditions at times other than high water; the fact that no mid-stream station was worked during Survey B5 provides an additional difficulty. Using the C1 graph (Figure 21), the results of the B4 and B2 surveys were then corrected to give the assumed overall variation in salinity along the length of the estuary at high water. The corrections actually applied were $+0 \cdot 735^0/_{00}$ and $-0 \cdot 288^0/_{00}$ for B4 and B2 respectively. No corrections were applied to the results of Surveys B1 and B3, which were carried out in the mouth of the estuary where the river flow will have had proportionately less effect. The results of this work are shown in Figures 30-32, representing conditions at H.W. −2, H.W., and H.W. +2, respectively. These salinity distributions have been deduced from the results of Operation 4 only for times within two hours of high water, since at other times the river flow will have been more important and it becomes very difficult to make a realistic correction for this.

Fig. 30. *Distribution of surface salinity* ($^0/_{00}$) *deduced from the results of Operation* 4 *for two hours before high water.*

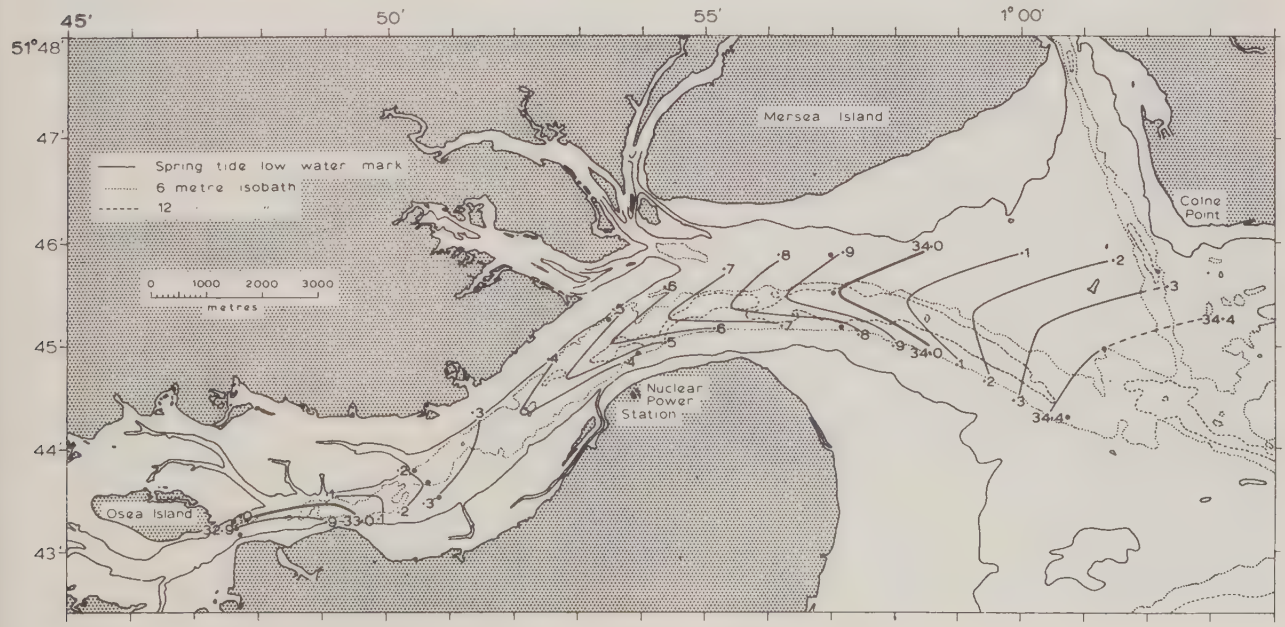


Fig. 31. *Distribution of surface salinity* ($^0/_{00}$) *deduced from the results of Operation* 4 *for high water.*

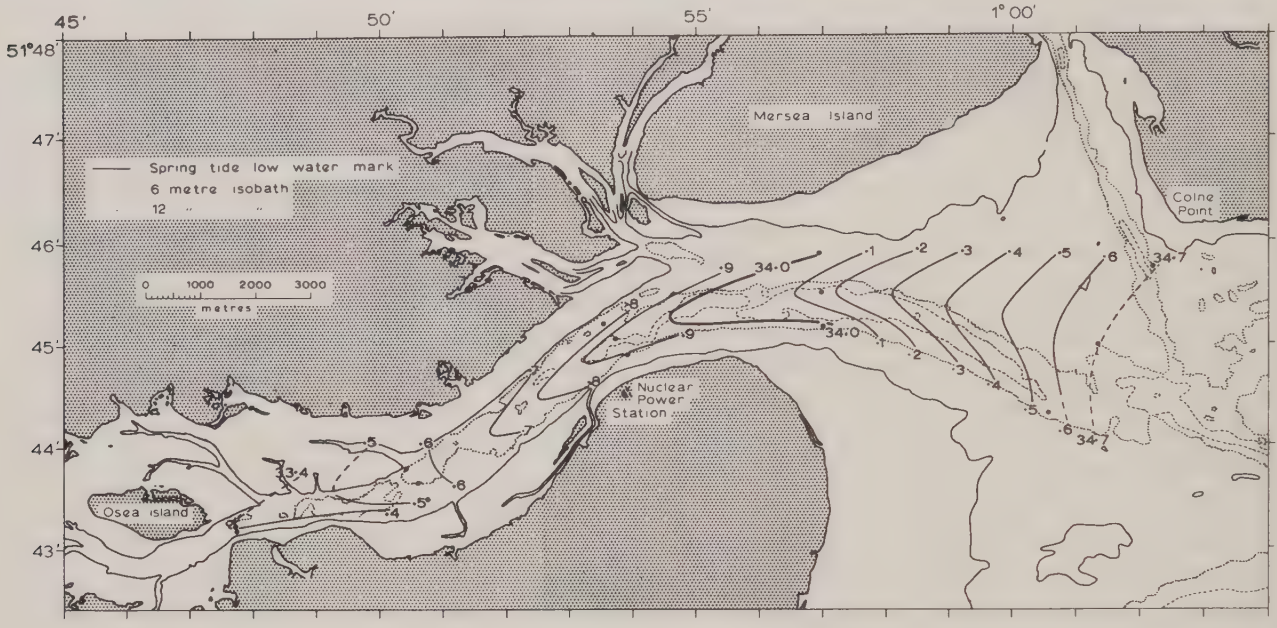


Fig. 32. *Distribution of surface salinity* ($^0/_{00}$) *deduced from the results of Operation* 4 *for two hours after high water.*

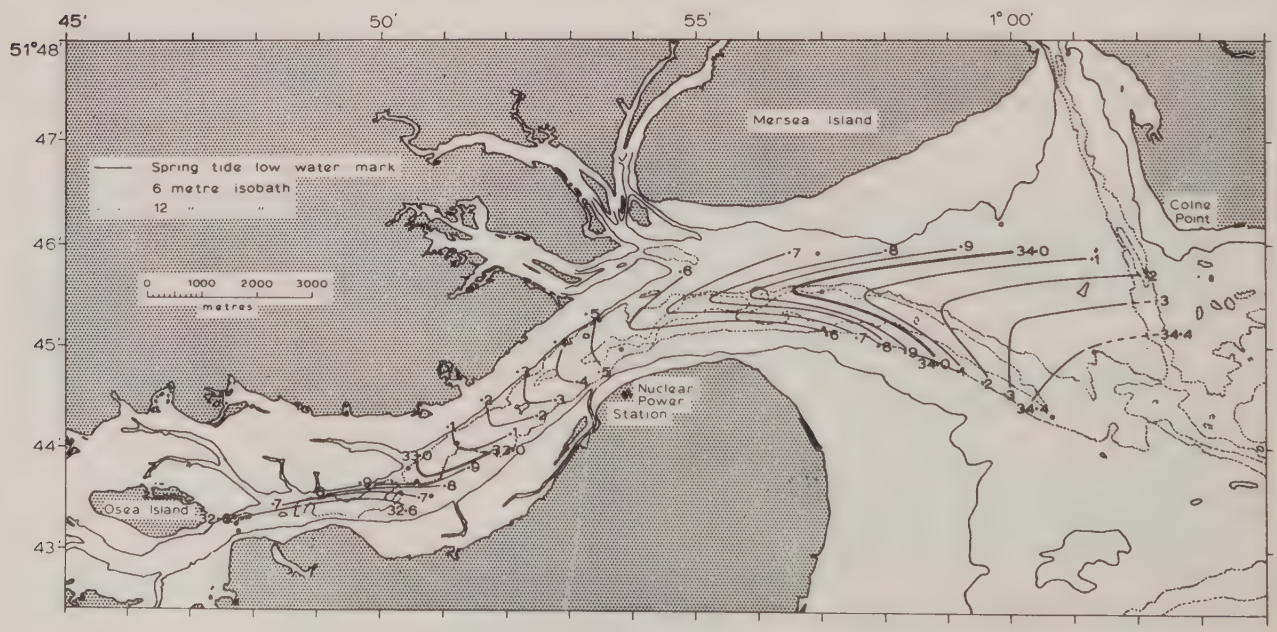


Fig. 33. *Distribution of surface salinity ($^0/_{00}$) deduced from the results of Operation 2 for four hours before high water.*

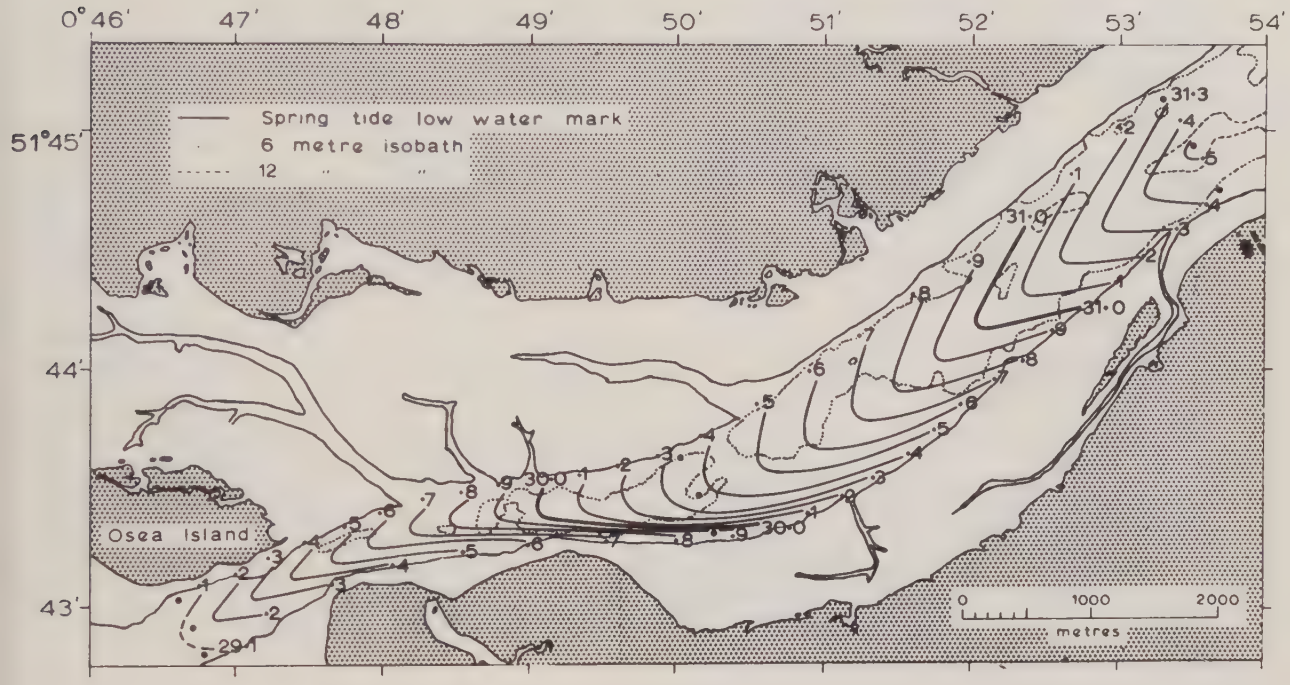


Fig. 34. *Distribution of surface salinity ($^0/_{00}$) deduced from the results of Operation 2 for two hours before high water.*

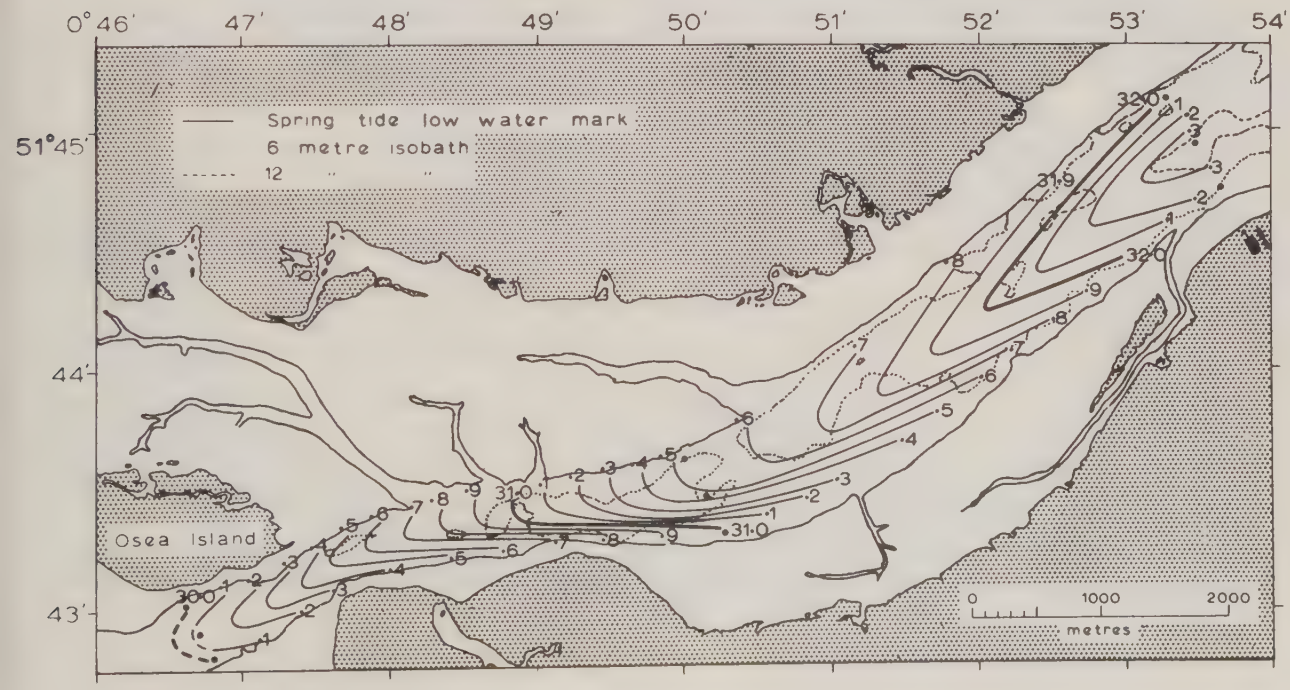


Fig. 35. *Distribution of surface salinity* ($^0/_{00}$) *deduced from the results of Operation 2 for high water.*

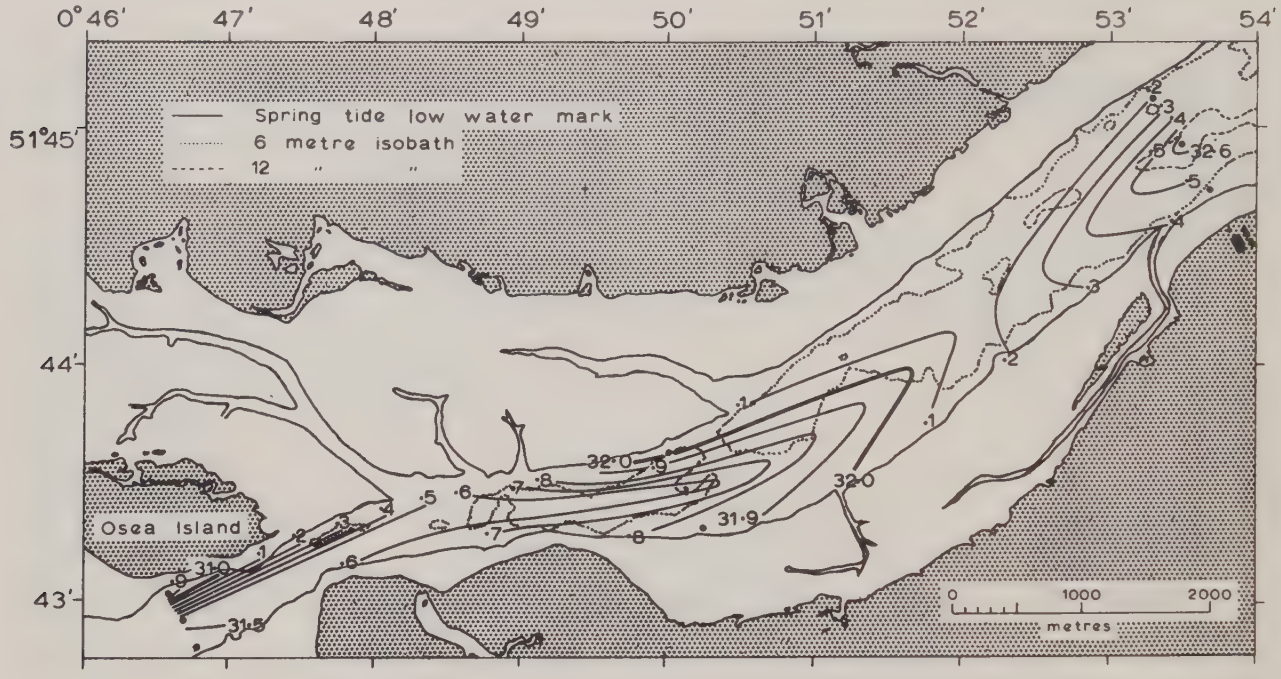


Fig. 36. *Distribution of bottom salinity* ($^0/_{00}$) *deduced from the results of Operation 2 for high water.*

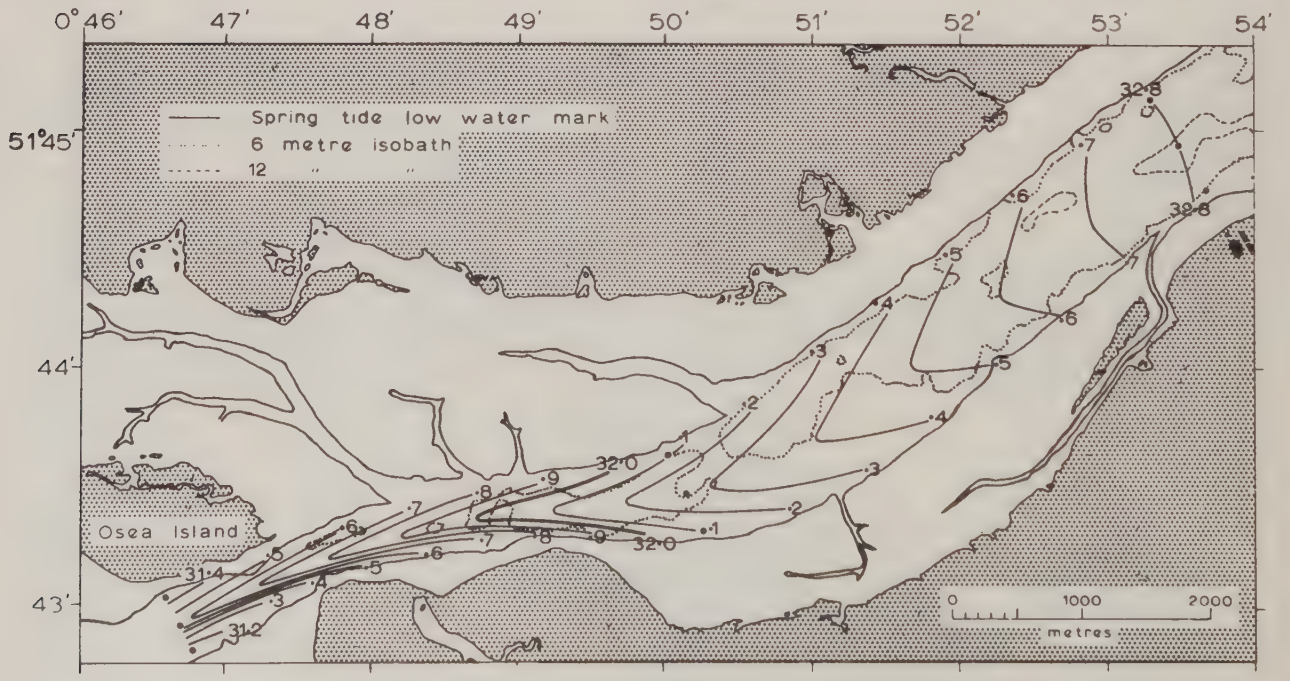
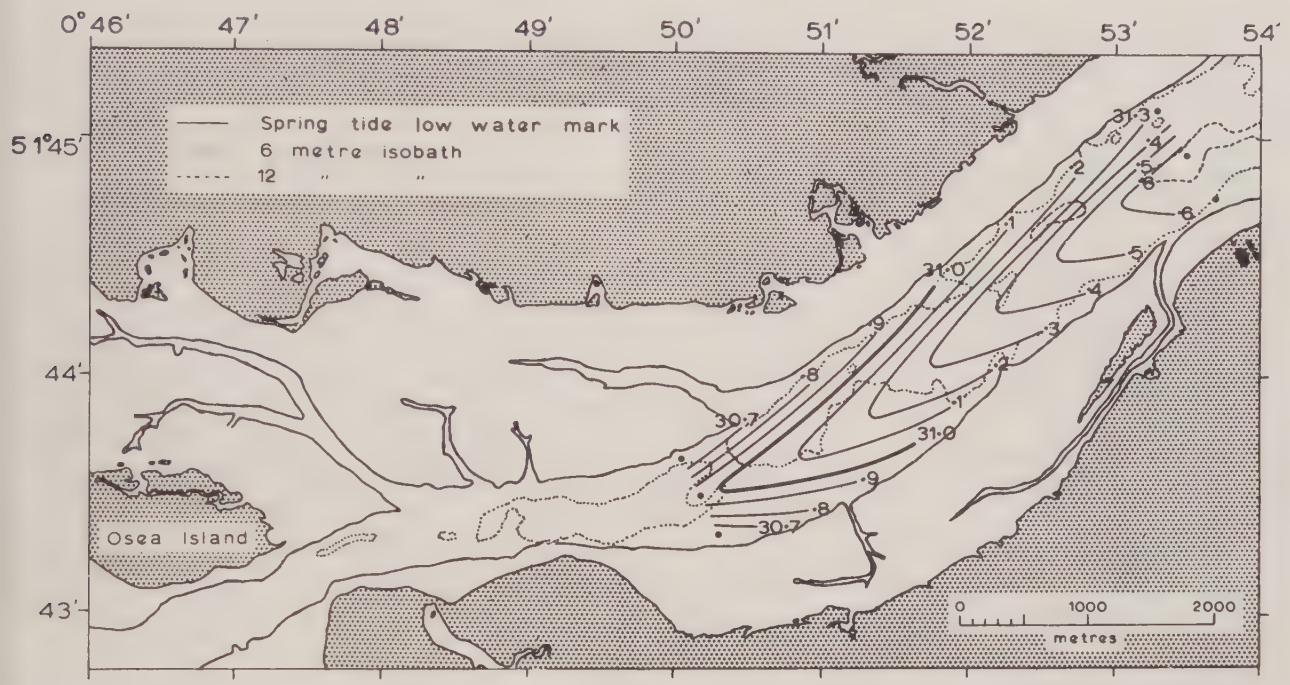


Fig. 37. *Distribution of surface salinity* ($^0/_{00}$) *deduced from the results of Operation 2 for two hours after high water.*



A further source of relevant information was the results of the Onaway survey of March 1960 (Operation 2). This survey was intended only as a preliminary to the more thorough work that was to follow, but it has the advantage that readings were spread over only two days and are therefore more comparable than those of the later survey. Unfortunately the Onaway results cover only a part of a tidal cycle, but, since this provides information over a part of the tide that is most difficult to deduce from the November results, the diagrams obtained are reproduced here (Figures 33-37). These refer to H.W. −4, H.W. −2, H.W. and H.W. +2 for the surface isohalines and H.W. only for the bottom ones. This last diagram was drawn because the surface results at H.W. indicate a rather peculiar situation, probably resulting from the presence of some surface water of lower salinity in the immediate vicinity of the centre station opposite Thirslet Creek. This illustrates the danger of drawing these diagrams on the basis of information obtained from a rather small number of comparatively widely spaced stations. It is, however, satisfactory to see that the bottom isohalines represent what we might regard as a reasonable distribution for this situation.

These results for the variation of the surface-water salinity are discussed in the following section, where they help to illustrate the circulation of water in the estuary.

The discussion of the results has revealed no evidence for any appreciable and persistent vertical stratification, although significant and often unexpected salinity differences between surface and bottom have been met. This analysis has thus suggested that, although we may often find that water velocity decreases appreciably with increasing depth, the integrated water movement over a tidal cycle should show little dependence on depth.

Some horizontal stratification has been indicated by the salinity and temperature distributions in the vertical transverse sections, and this suggests that there may be a significant horizontal stratification of flow.

In estuaries in the northern hemisphere there is often a tendency for the flow of river water to the sea to keep to the right-hand bank. It has been shown that the rotation of the earth in conjunction with the water movement could produce a Coriolis force giving rise to this effect. In a typical situation there would be a residual ebb of lower-salinity water along the right-hand shore and a corresponding flood of higher salinity along the left-hand shore. Since the river flow into the Blackwater is small we might expect a correspondingly small lateral stratification of flow; on the other hand the tidal velocities encountered are quite large and it is possible that this will cause some lateral separation of the main ebb and flood water movements, the latter tending to be to the north of the former.

In the light of the above discussion we must now examine the results for further evidence concerning residual flow and any variation of this with depth or position across the estuary. It is natural to consider first the results obtained using the current meters.

(i) *Calculation of residual flow from current meter readings*

In calculating residual flow we shall consider a vertical area of cross section of the estuary extending $\frac{1}{2}$ metre in both horizontal directions normal to the flow and having the depth of the estuary at the position considered. Although the magnitude of this area will vary over a tidal cycle, the water movement through it will always be typical of that particular position in the estuary. The residual flow will be taken as the net volume flowing through this area during one complete tidal cycle.

Notation

h	=	depth of water		T	=	time for one tidal cycle
t	=	time	$\bar{u}$	=	depth mean velocity of water	V_R	= residual flow

The instantaneous flow for a particular position will be given by $h\bar{u}$ and the net flow over a tidal cycle by

$$V_R = \int_0^T h\bar{u}\, dt.$$

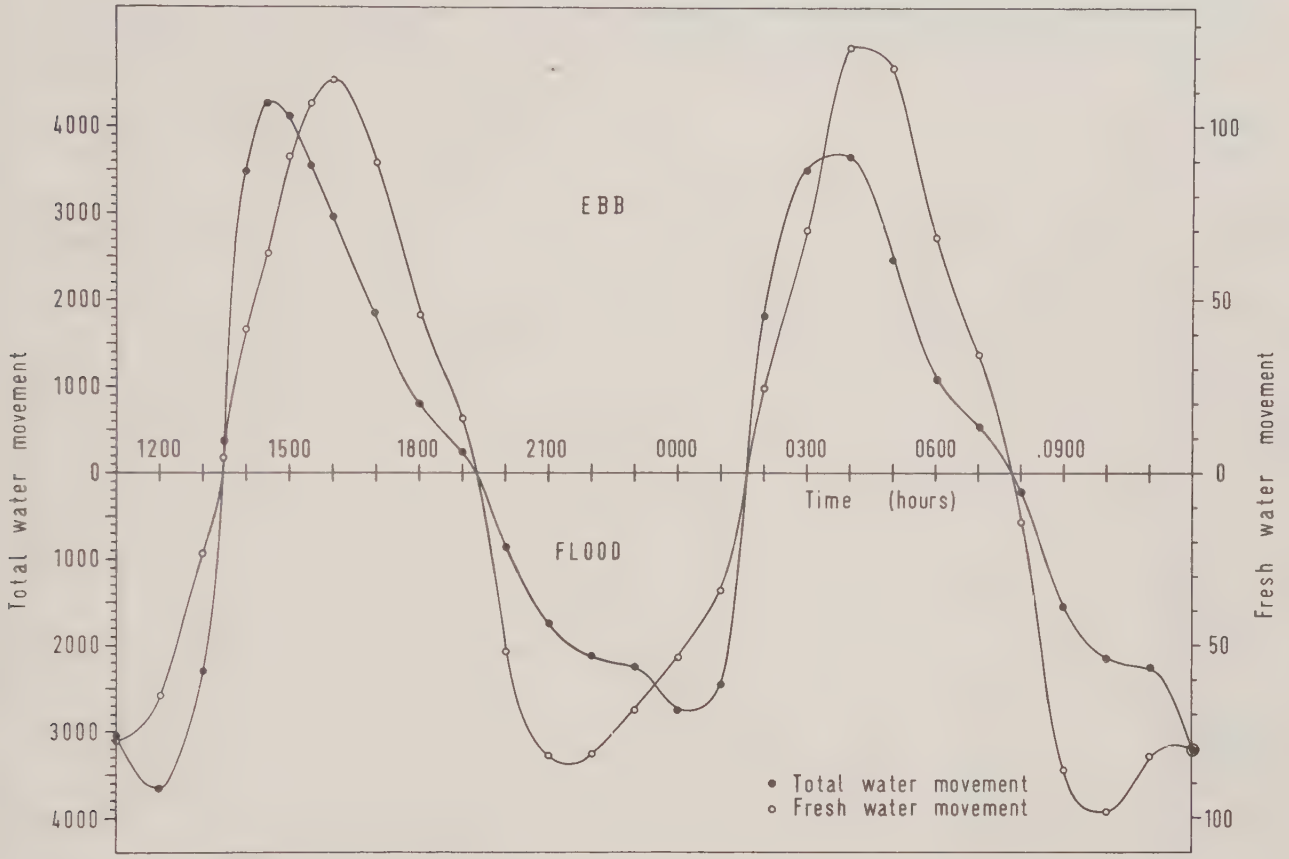
In practice, this summation has had to be performed graphically, the areas under graphs of $h\bar{u}$ plotted against t being measured with a planimeter. The result of this summation should be the net volume of water passing through the respective area during each tide. Although, in some connections, it might be preferable to convert this volume transport into an equivalent mean velocity, this has not been thought to be worthwhile in this case where the main interest in the residual flow is with regard to its importance in the transport of water and associated matter in the estuary.

If we denote the areas under the graph (Figure 38) for ebb and flood as Δ_{EBB} and Δ_{FLOOD} respectively, it is clear that

$$\int_0^T h\bar{u}\, dt = \Delta_{EBB} + \Delta_{FLOOD}$$

where Δ_{FLOOD} is essentially negative. It is found that, algebraically, $(\Delta_{EBB} + \Delta_{FLOOD}) \ll \Delta_{EBB}$ and numerically $\Delta_{EBB} \simeq \Delta_{FLOOD}$.

Fig. 38. *Water movement (in arbitrary units) over two tidal cycles at the mouth of the estuary (Operation 5, Survey C1).*



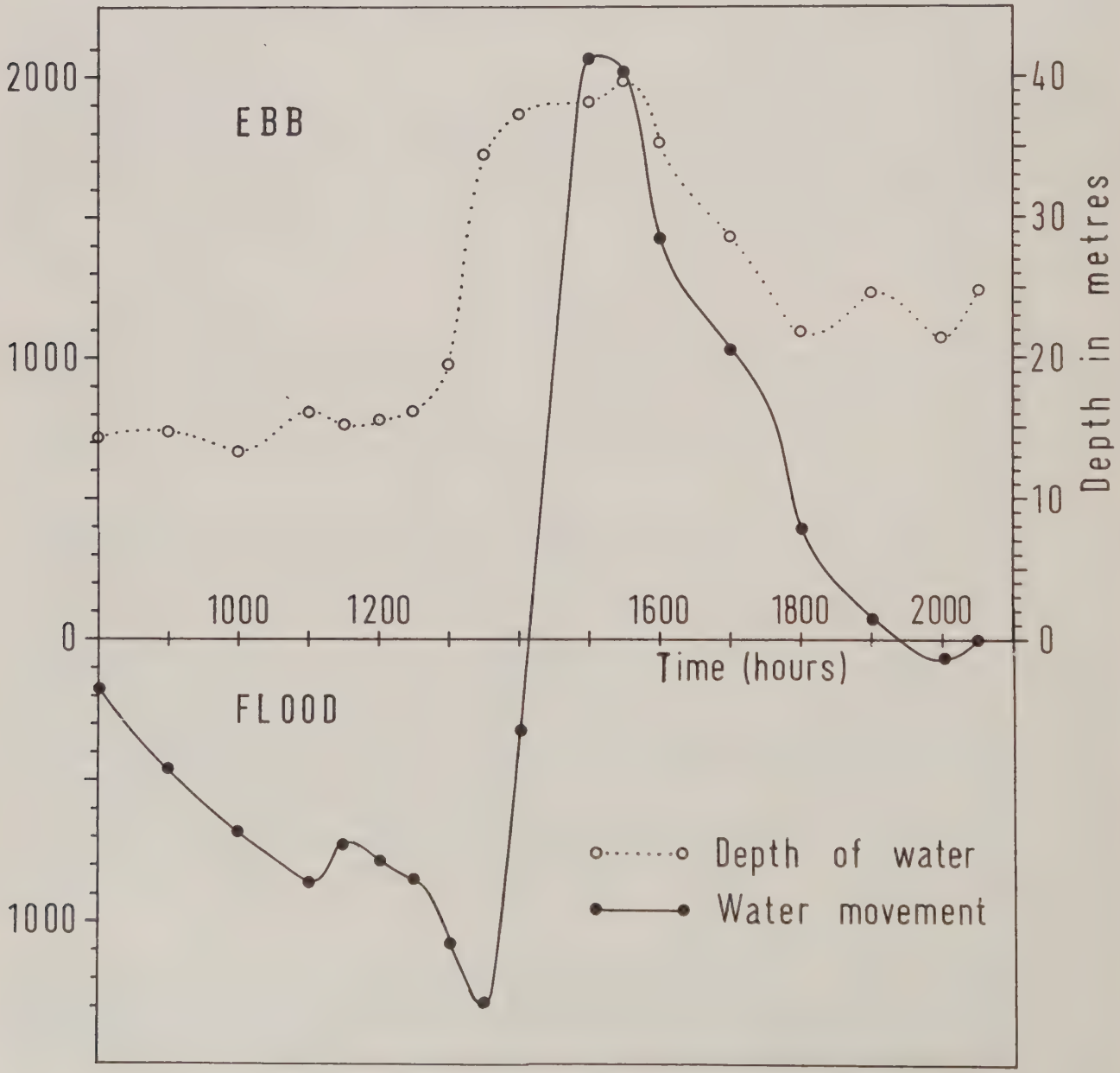
Thus the required result for residual flow is, in fact, given by the small difference between two quite large quantities. Values actually obtained for Δ_{EBB} and Δ_{FLOOD} during Operation 4 are given in Table 5. In interpreting these values it is necessary to take into account the accuracy of the measurements involved. Two possible sources of error were the measurement of depth and of water velocity, of which the former probably introduces the larger fractional error. Under the working conditions in the estuary it is considered that an error of $\pm 0{\cdot}3$ m was quite likely when determining depth with the echo sounders. The error involved in the measurement of water velocity was probably no larger than ± 2 cm sec^{-1}. Taking these two sources of error into consideration the possible fractional error in estimating Δ_{EBB} may be taken as 5%. This would mean that differences as large as 10% of Δ_{EBB} could arise when estimating the difference between the ebb and flood areas under the graph. It would therefore seem reasonable to regard all differences of less than 5% of Δ_{EBB} as giving no clear evidence of residual flow.

The estimate of error is necessarily approximate but helps to give some idea of the probable error associated with the results quoted in Table 5. In three cases, *TELLINA* and *WYSTRYS* (B5) and *JASSA* (B3), the differences between the areas Δ_{EBB} and Δ_{FLOOD} were all less than 2% of Δ_{EBB} and in these cases zero residual flow has been assumed.

A second factor which has had to be considered results from the swinging of the boats on the tide, since, as mentioned above, it was not considered safe to moor the boats from both ends. In positions where local variations in depth are likely to be small compared with total depth this is of no great importance, but there were cases where the depth of water under the boat during flood was appreciably different

from that encountered during ebb. As a check on this effect $\int$ hdt was evaluated for both ebb and flood periods of the tidal cycle. In cases where there was a significant difference between these two values, and the residual flow (Δ_{EBB}—Δ_{FLOOD}) that was predicted was small, the result for the latter was rejected; in such cases no result is recorded in the final column of Table 5. Figure 39 illustrates the variation of depth that was recorded at the northern station of Survey B2. The observations of *WYSTRYS* in Survey B4 illustrate a particularly extreme example of this effect, the average depth during flood being about 0·58 of that during ebb. In such cases it was considered impossible to interpret the results in terms of residual flow.

Fig. 39. *Variation of depth and water movement over one tidal cycle recorded close to the northern shore* (*Operation* 4, *Survey B*2).



(*ii*) *Direction of residual flow*

Since the accuracy of the results for magnitude of residual flow was comparatively low there seems to be no point in evaluating the direction of this flow precisely. Apart from the main difference between ebb and flood little account has been taken of minor changes in direction of flow, and the directions of the residual flow vectors (Figure 40) must be regarded as approximate.

(*iii*) *Evidence of residual flow from the surface diagrams*

The evidence for residual flow based on the current measurements is clearly incomplete; this was one reason for trying to plot the plan view isohalines in the hope that these would provide further useful evidence.

From the current measurements the circulation in the mouth of the estuary seems fairly clear and is what would be expected as a result of the Coriolis effect. Inside the estuary the situation is much more obscure, the only marked residual found being that at the position of *TELLINA* during Survey B2. The presence of this residual ebb at midstream in this section implies that there must be a residual flood at some other point either to north or south of *TELLINA*'s position. However the significance of this particular result is reduced by the inconclusive results of the other two stations on this occasion. The resultant ebb at *TELLINA*'s position may have been produced by a difference in height of successive low waters. Unfortunately no tide gauge record is available for this survey, so we can only say that it appears likely that there is some residual ebb at this position but that it may not be as large as that deduced from the recorded observations. In this region we find the isohalines suggesting a considerable flow of water on to the Goldhanger-Thirslet Creek flats during the flood tide; this has no direct counterpart in a corresponding outflow during the ebb (Figure 27 (ii)). It is therefore suggested that in this section there is a residual flood on to the flats bordering the northern shore, the water leaving the flats again by a different path.

In the Osea Island transect a small residual flood was detected near the northern shore, the other results not being significant. It seems highly probable that a corresponding residual ebb exists nearer to the southern shore. Some evidence for this is provided by the November isohalines (Figure 32) which at H.W. +2 indicate the southern shore to be markedly less saline than the north, and a similar conclusion could be drawn from the discussion of the distribution of salinity in the vertical plane across this section for both high- and low-water conditions (Figure 19).

Table 5. *Calculation of residual flow from current meter readings obtained during Operation* 4

Vessel	Survey	Δ_{EBB} ($m^3 \times 10^4$)	Δ_{FLOOD} ($m^3 \times 10^4$)	V_R ($m^3 \times 10^4$)	$\int$ hdt EBB (arbitrary units)	$\int$ hdt FLOOD (arbitrary units)	Predicted value of residual flow per tide ($m^3 \times 10^4$)
TELLINA	B1	9·85	− 6·23	+ 3·62			+3·6
	B2	10·01	− 7·34	+ 2·67	5·05	4·65	+2·7
	B3	6·77	− 7·98	− 1·21			−1·2
	B4	3·16	− 3·40	− 0·24	2·08	2·04	−0·2
	B5	12·80	−13·16	− 0·36	5·61	5·29	0
WYSTRYS	B1	10·20	− 6·41	+ 3·79			+3·8
	B2	6·37	− 5·91	+ 0·46	3·64	3·23	?
	B3	4·85	− 3·14	+ 1·71			+1·7
	B4	4·45	− 6·34	− 1·89	1·93	3·35	?
	B5	5·07	− 4·98	+ 0·09	4·17	4·17	0
JASSA	B1	7·52	−11·72	− 4·20			−4·2
	B2	5·71	− 4·87	+ 0·84	4·02	3·45	?
	B3	2·54	− 2·58	− 0·04			0
	B4	5·97	− 6·34	− 0·37	2·30	3·35	?

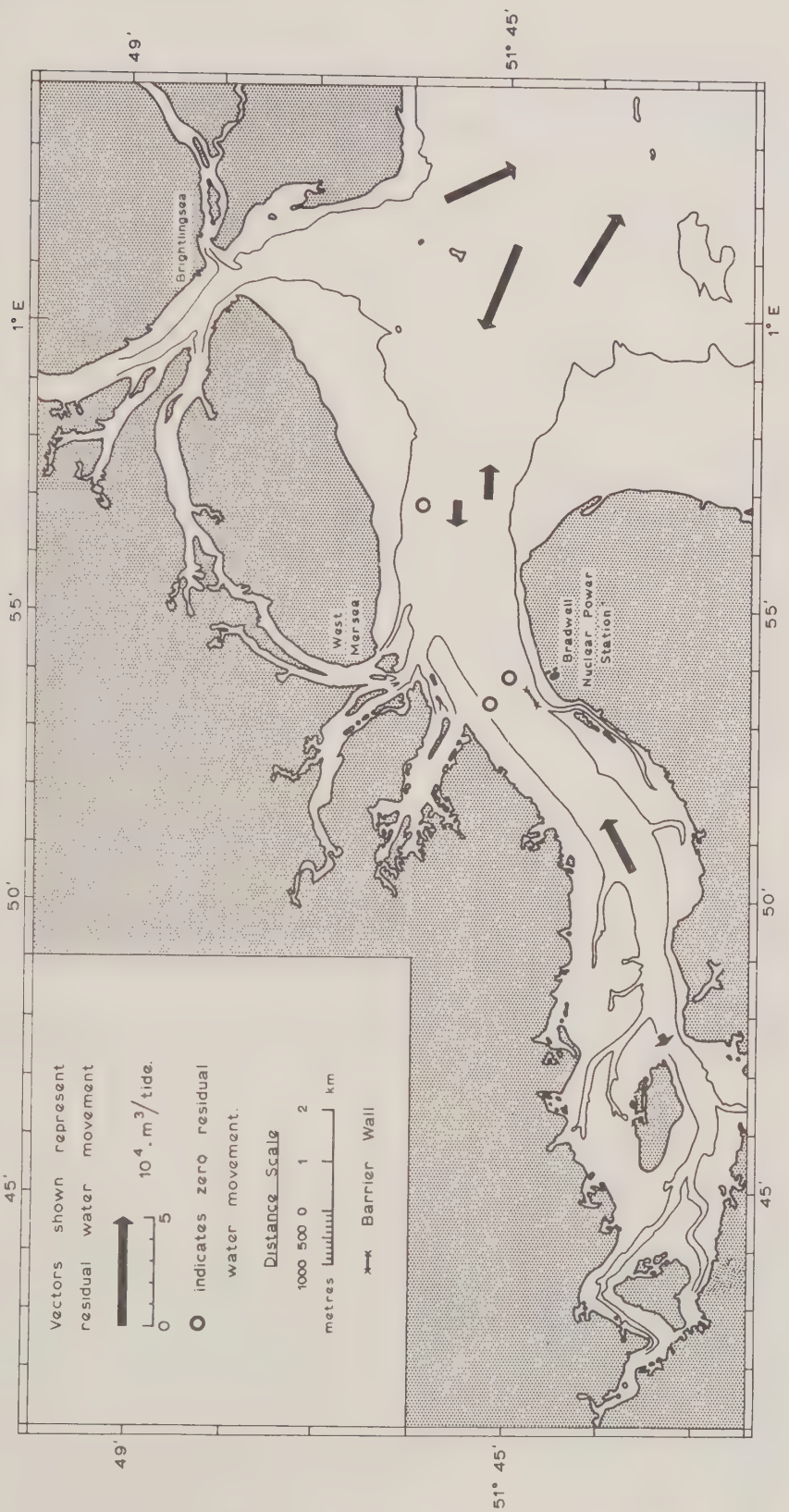


Fig. 40. *Calculated values of residual flow in the estuary.*

ESTIMATION OF EXCHANGE OF WATER BETWEEN THE ESTUARY AND THE SEA

In the following discussion of exchange the mouth of the estuary has been taken to be at the power station section, and all references to the volume of water contained within the estuary refer to the volume upstream from the power station.

The estimation of the extent to which water from the estuary disperses into sea water associated with the nearby coastal region is a matter of some difficulty. For this reason several methods have been considered, each of which might be expected to yield some significant information.

METHOD I
CONSIDERATION OF KETCHUM'S SEGMENTATION METHOD

The first attempt to tackle this problem was based upon a method suggested by Ketchum (1951*a*), who had tried to improve the earlier tidal prism method by introducing the idea of segmentation of the estuary. Although this method was applied quite successfully by Ketchum (1951*b*) to three dissimilar estuaries there were reasons for doubting its relevance to the Blackwater. In the case of the three estuaries considered by Ketchum the ratio of total tidal prism : river flow per tide covered a range of from 279 to 15; this ratio is 4 000 for the Blackwater. It has also been found (Stommel 1953) that the theory does not apply in the case of the Severn estuary, although this seems to have all the essential characteristics assumed by Ketchum. An attempt to apply this theory to the Blackwater was made by Parr (Appendix III), but it seems that we can conclude no more from this than that Ketchum's theory is not applicable in this case.

METHOD II
USING OBSERVATIONS OF SALINITY WITHIN THE ESTUARY

A second approach to this problem was to use the salinity data in order to calculate the volume of water escaping during each tidal cycle. This was also mentioned by Ketchum and was considered by Parr. In the case of the Blackwater the indication was that between 2% and 4% of the high-water volume of the estuary is lost to the sea during each tidal cycle. This method will be mentioned again when discussing an approach which makes use of the total freshwater budget of the estuary, since Method II may be regarded as a special case of the latter at a time when the salinity of the estuary is constant.

METHOD III
CALCULATION OF LONGITUDINAL EDDY DIFFUSION COEFFICIENTS

In commenting on the difficulties of applying theories such as those put forward by Ketchum, Stommel (*loc. cit.*) has suggested that a more promising approach would be to calculate, from the observed distribution of river water, values of turbulent diffusion coefficients at various points in the estuary. This approach also was tried by Parr, who calculated values of the longitudinal coefficient of eddy diffusivity from the equation

$$K_x = \frac{\bar{R}\bar{S}}{A\dfrac{\overline{\delta S}}{\delta x}}$$

where R = rate of influx of fresh water
$\bar{S}$ = mean salinity over a vertical section over an integral number of tidal cycles
A = mean cross-sectional area of estuary at position being considered
x = distance measured along centre line of estuary towards the sea.

The results of this work are given in Table 12 (Appendix III), together with results obtained by Bowden (1963) for the Thames estuary. The values for the low river flow on the Thames will be seen to be of the same order of magnitude as the Blackwater results. According to these results longitudinal eddy diffusion is greater in the centre reaches of the Blackwater than at the mouth.

METHOD IV
CONSIDERATION OF THE EFFECT OF BOTTOM FRICTION

The effect of bottom friction was also considered by Bowden who derived values for the longitudinal diffusion coefficient on the assumption that a distortion of the salinity profile, resulting from bottom friction, would play an important part in the horizontal diffusion process. Parr also considered this possibility and his results are included in Table 12. These confirm Bowden's conclusion that bottom friction is not a main cause of the large coefficients of horizontal eddy diffusion that are operative in estuaries.

METHODS V and VI

In the following two methods, as in Method II, the estuarine water has been regarded as a mixture of fresh water and sea water. The volume of fresh water V_f in a volume V of sea water will be given by

$$V_f = V\frac{S_{sea} - S_{est}}{S_{sea}}$$

or the fraction of a given sample of mixed water that is fresh by

$$f = \frac{S_{sea} - S_{est}}{S_{sea}}$$

where S_{sea} = salinity of 'pure' sea water
S_{est} = salinity of estuarine water.

A knowledge of salinity values should therefore make it possible to use the fresh water as an indicator of water movements.

METHOD V
DEDUCTION OF FRESHWATER RESIDUAL FLOW OVER ONE OR TWO TIDES

We have discussed the deduction of residual flow from the graph of total water movement over a tidal cycle (Figure 38). A similar graph can be plotted for the function fuh which should in principle represent the movement of the freshwater component corresponding to this total water movement. These two graphs represent two fundamental aspects of the water movement through a given section. The total water movement graph indicates any residual motion of mixed water, whilst the freshwater movement graph should indicate the extent to which water returning on the flood is of a different composition from water flowing out on the ebb. Exchange between ebb waters and the sea will have played a large part in producing this change in composition.

Suppose A_1 = total water outflow on an ebb tide
A_2 = total water inflow on a flood tide

and B_1 = freshwater loss on an ebb tide
B_2 = freshwater inflow on a flood tide

then $\frac{A_1 - A_2}{A_1}$ = a, representing the fraction of the ebb that does not return

and $\frac{B_1 - B_2}{B_1}$ = b, representing the fraction of the freshwater component of the ebb that does not return.

A value of a other than zero will indicate some residual flow of water past the station that is being considered. This residual flow will contribute to the value of b but this second constant will also depend upon the degree of mixing between the ebb tide and the offshore waters. The constant b will also be taken to represent the fraction of the ebb as a whole that does not return on the next flood, some of it being replaced by 'sea' water. The main interest in this context is that part of b which results from exchange with the sea as opposed to residual flow. This will correspond to the fraction of the ebb that is lost by mixing with the sea, and will be given by $(b - a)$.

In applying this method we must remember that we are using the freshwater content of the estuarine water as an indicator for the total water movement. Ideally, for this approach to be successful the fresh water should be uniformly distributed throughout the estuary at high water. This, as we have seen, is not the case (Figure 21) and particularly so in winter and spring; at high water the tendency will be for most of the fresh water to be found near the head of the estuary. Since this water will have least chance of exchange with the sea the expression $(b - a)$ defined as above would be expected to give markedly low values for the exchange coefficient. In an attempt to overcome this, water movements have been considered within a given interval of high water. Thus, if we consider water movements within τ hours of high water we have

$$A_1\tau - A_2\tau = \int_{HW-\tau}^{HW+\tau} h\bar{u}dt$$

and

$$A_1\tau = \int_{HW}^{HW+\tau} h\bar{u}dt$$

and we may write

$$\alpha = \frac{\int_{HW-\tau}^{HW+\tau} h\bar{u}dt}{\int_{HW}^{HW+\tau} h\bar{u}dt}$$

where α corresponds to a (above) but over the restricted time interval chosen. Likewise, if β corresponds in a similar way to b above, we may write

$$\beta = \frac{\int_{HW-\tau}^{HW+\tau} fh\bar{u}dt}{\int_{HW}^{HW+\tau} fh\bar{u}dt} \quad ;$$

if we write $$\lambda = \frac{\int_{HW}^{HW+\tau} h\bar{u}dt}{\int_{HW-\tau}^{HW} h\bar{u}dt}$$

and $$\mu = \frac{\int_{HW}^{HW+\tau} fh\bar{u}dt}{\int_{HW-\tau}^{HW} fh\bar{u}dt}$$

then $$\alpha = 1 - \frac{1}{\lambda}$$

and $$\beta = 1 - \frac{1}{\mu}.$$

Thus exchange with the sea is given by

$$\beta - \alpha = \frac{1}{\lambda} - \frac{1}{\mu}$$

$(\beta - \alpha)$ representing the fraction of the ebb that is lost from the estuary as a result of mixing of ebb waters with the sea.

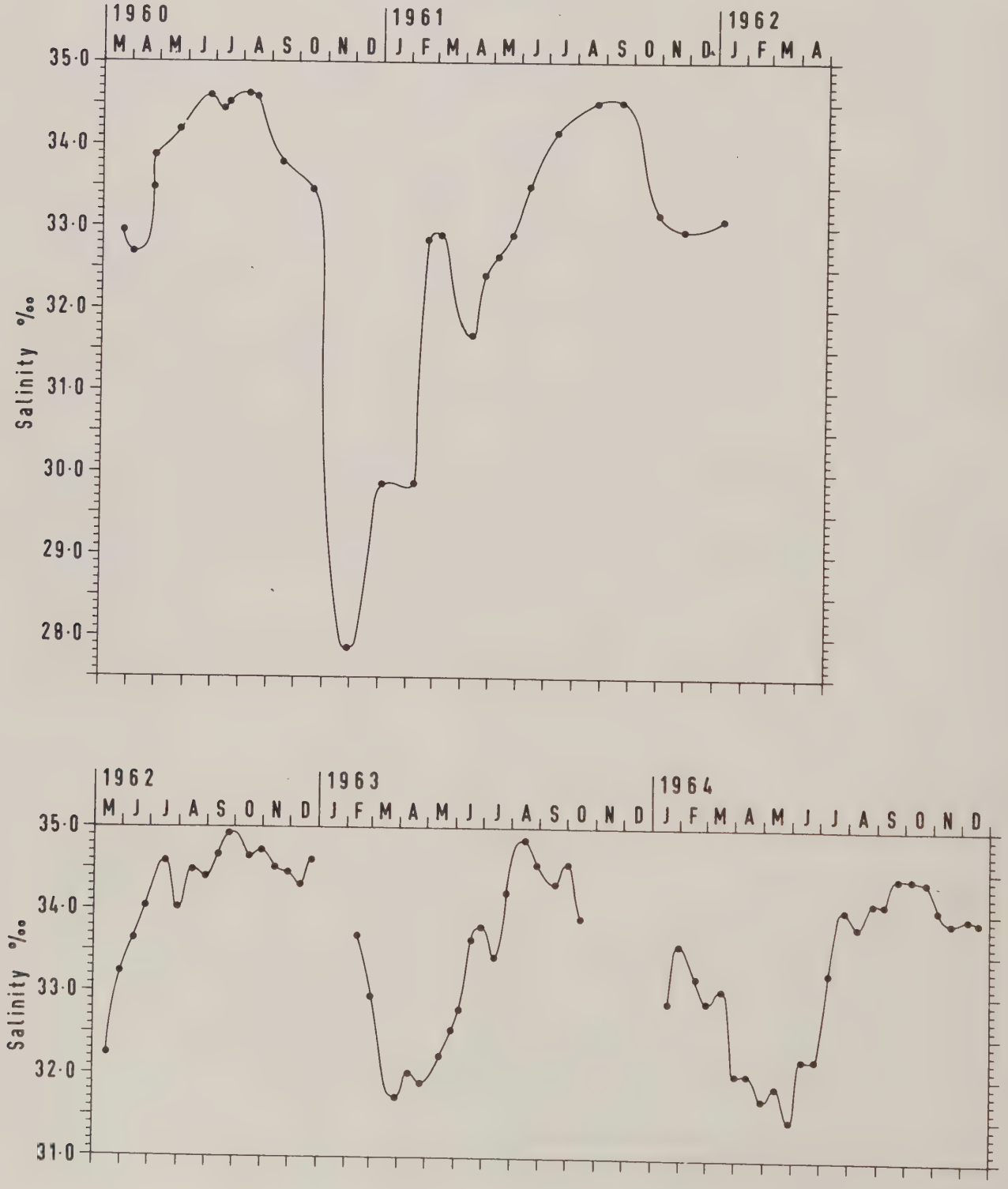
Since β and α depend upon ratios of areas under the graph the vertical scale is not important and arbitrary units have been used in Figure 38; the same unit has, however, been used for both total and freshwater flow.

Using the graphs of Figure 38 and similar graphs drawn for Surveys A1, A2 and C2 the relevant areas were measured with a planimeter for the time interval from three hours before to three hours after high water. From these measurements of area were obtained the values of μ and λ set out in Table 6. The time interval used in this calculation corresponds to the passage of a volume of water equal to approximately two thirds of the total tidal prism.

Table 6. *Ratios of ebb to flood water movements at the mouth of the estuary* (*Station* 5)

Operation	Survey	S_{sea} (‰)	λ	$\frac{1}{\lambda}$	μ	$\frac{1}{\mu}$	$\frac{1}{\lambda} - \frac{1}{\mu}$	Fraction of high-water volume lost on each tide
3	A1	34·75	0·94	1·07	1·08	0·92	0·15	0·10
3	A2	34·77	0·80	1·25	0·86	1·16	0·09	0·05
5	C1	33·95	1·29	0·78	1·50	0·67	0·08	0·06
5	C2	34·03	1·11	0·90	1·19	0·84	0·06	0·03

Fig. 41. *Variation of salinity at the barrier wall at high water over the period since March 1960. This graph is based upon records kept by C.E.G.B. and is reproduced here by kind permission of the Director of C.E.R.L., Leatherhead, Surrey.*



The use of this particular time interval would seem to be a reasonable compromise. If too short an interval had been used then too large a value for the exchange would have been obtained, since the calculation would have applied only to water which flowed past the mouth of the estuary at about high water. On the other hand it has already been explained that a calculation based on results for the whole tidal cycle would give too low a value for the exchange.

In order to compare the results of this method with those obtained using the total water budget of the estuary (Method VI, below) it is necessary to multiply by a factor depending upon the ratio between the total tidal prism and the total high-water volume of the estuary. This ratio is 0·70 for spring tides and 0·53 for neap tides (from Table 10, Appendix III). The result of applying this factor is shown in the last column of Table 6. In considering the significance of these results we must remember that the accuracy will depend upon the accuracy of determination of $(S_{sea} - S_{est})$. The values assumed for S_{sea} are given in Table 6 and are the means of the maximum value of salinity recorded in the estuary for the period under consideration and the salinity value recorded at the same time at the Galloper Lightvessel. Since, for the August surveys, the difference between the salinity of the estuary and that of the sea is small, the fractional error consequent upon any error in estimating S_{sea} is likely to be proportionately high. The main interest, therefore, must centre upon the results of Operation 5, carried out in the winter, when the salinity of the estuary was appreciably less than that of the sea. It will be seen in the next section that predictions of a degree of exchange of the same order are obtained using a method based upon the total water budget of the estuary.

METHOD VI
CALCULATION OF THE FRESHWATER BUDGET OF THE ESTUARY OVER A PERIOD OF SEVERAL DAYS

Values of salinity at the barrier wall and at other points in the estuary have been recorded by G.E.G.B. on numerous occasions since April 1960 (Figure 41) (Spencer 1964 and 1965). It was considered that the salinity in the vicinity of the barrier wall at high water should give some measure of the freshwater content of the estuary, and that changes in this salinity must depend upon the rate at which the total freshwater content of the estuary can vary.

In order to produce an equation relating the high-water salinity at the barrier wall to the exchange coefficient between the estuary and the sea, it has been necessary to adopt a simplified view of the estuary. It has been assumed, for the purpose of this calculation, that the water in the vicinity of the barrier wall is representative of all the water within the estuary. Although this assumption will clearly lead to quite false values of the freshwater content of the estuary it is nevertheless considered reasonable in the circumstances. It must be remembered that as far as exchange with the sea is concerned the most important part of the high-water content of the estuary is that which is nearest the sea. Also the method is concerned with changes in the freshwater content rather than its absolute value. The assumption will, however, tend to produce errors in the exchange coefficient such that calculated values may be expected to be high at times of increasing land run-off and low when land run-off is decreasing. It is hoped that by taking a considerable number of periods, spread over three or four years, cases of increasing, decreasing and of almost constant land run-off will be included. The results collectively should provide some useful indication of the value of the exchange coefficient.

Suppose V = high-water volume of the estuary

V_n = volume of fresh water within the estuary, estimated as described above, after 'n' tides.

r = net freshwater input to estuary per tide, resulting from rainfall, river flow and evaporation.

Thus, if we assume the high-water volume of the estuary to remain constant, as a result of river flow a volume r of mixed water must leave the estuary every tide. The fresh water lost from the estuary on each tide corresponding to this will be given by

$$\left(\frac{V_n}{V}\right)r.$$

There will also be an additional loss of fresh water as a result of mixing with the sea. Suppose that over one tide a fraction ε of water in the estuary is permanently lost to the sea; then after one tide the freshwater content of the estuary should be given by

$$V_1 = V_0(1-\varepsilon) + r\left(1 - \frac{V_0}{V}\right)$$

$$= V_0\left(1 - \varepsilon - \frac{r}{V}\right) + r.$$

Similarly $V_2 = V_1(1-\varepsilon) + r\left(1 - \frac{V_1}{V}\right)$

$$= V_1\left(1 - \varepsilon - \frac{r}{V}\right) + r$$

$$= V_0\left(1 - \varepsilon - \frac{r}{V}\right)^2 + r\left(1 - \varepsilon - \frac{r}{V}\right) + r,$$

and $V_3 = V_2\left(1 - \varepsilon - \frac{r}{V}\right) + r$

$$= V_0\left(1 - \varepsilon - \frac{r}{V}\right)^3 + r\left(1 - \varepsilon - \frac{r}{V}\right)^2 + r\left(1 - \varepsilon - \frac{r}{V}\right) + r.$$

Put $\xi = 1 - \varepsilon - \frac{r}{V}$;

then $V_n = V_0\,\xi^n + r(1 + \xi + \xi^2 + \xi^3 + \ldots\ldots \xi^{n-1})$,

and $V_0 - V_n = V_0\left(1 - \xi^n\right) - r\frac{1-\xi^n}{1-\xi}$,

or $1 - \frac{V_n}{V_0} = \left(1 - \xi^n\right) - \frac{r}{V_0}\left(\frac{1-\xi^n}{1-\xi}\right)$. (1)

$$\text{Now} \qquad V_0 = V\frac{S_{sea} - S_o}{S_{sea}}$$

$$\text{and} \qquad V_n = V\frac{S_{sea} - S_n}{S_{sea}}$$

where S_o and S_n refer to the salinity of the estuarine water at the beginning of the period and after n tidal cycles.

Thus equation (1) becomes

$$\frac{S_n - S_o}{S_{sea} - S_o} = \left(1 - \xi^n\right) - \frac{r\,S_{sea}}{V(S_{sea} - S_o)}\left(\frac{1 - \xi^n}{1 - \xi}\right)$$

$$\text{or} \qquad S_n - S_o = (S_{sea} - S_o)\,(1 - \xi^n) - \frac{r\,S_{sea}}{V}\left(\frac{1 - \xi^n}{1 - \xi}\right). \qquad (2)$$

This equation may, in principle, be solved for ξ and hence values of the exchange coefficient deduced. It is, however, doubtful whether the accuracy with which the various parameters are known justifies the use of this equation in every case. As explained below, S_{sea} is particularly difficult to assess, but some error is also likely to have arisen from the other salinity values which are needed for this calculation.

When the original salinity measurements were made it could not have been envisaged that they would be applied in this way and the titration techniques used in the analysis often produce errors in salinity as large as $\pm 0{\cdot}05\,^0/_{00}$ (Strickland and Parsons 1960). In the case of the earlier data, additional errors can arise from the fact that the salinity measurements often do not correspond to high-water conditions and it was necessary to estimate a correction for this.

Equation 2 may be simplified if we assume that

$$\varepsilon + \frac{r}{V} \ll 1$$

then, neglecting second order small quantities

$$S_n - S_o = \left(S_{sea} - S_o\right)n\left(\varepsilon + \frac{r}{V}\right) - \frac{nr}{V}S_{sea}$$

$$\text{i.e.} \qquad \varepsilon + \frac{r}{v} = \frac{1}{n(S_{sea} - S_o)}\left[S_n - S_o + \frac{nr}{V}\,S_{sea}\right]$$

$$\text{or} \qquad \varepsilon = \frac{1}{n(S_{sea} - S_o)}\left[S_n - S_o + \frac{nr}{V}\,S_o\right]. \qquad (3)$$

The values of the exchange coefficient quoted in Table 7 were obtained using the more exact equation (2) but it can be stated that for the period in 1964 the results obtained using equation (3) would have led to the same conclusions. The only significant difference between the results given by the two formulae occurs for a few of the 1961 results. In general, for readings at approximately fortnightly intervals and where the exchange predicted is less than 4%, the simplified equation will give results of sufficient accuracy.

Table 7. *Calculation of exchange of water between the estuary and the sea, using the freshwater budget of the estuary (Method VI)*

Date.	Salinity at power station S_n	Salinity at Galloper Lightvessel	Salinity assumed for coastal waters S_{sea}	$S_{sea}-S_o$	S_n-S_o	Total river flow 10^6m^3	Effective fresh water input to estuary 10^6m^3	River flow per tide 10^4m^3	Exchange coefficient (%)
18 August 1960	34·58	34·90							
15 September 1960	33·78	34·79	34·76	0·18	− 0·80	5·21	4·59	9·6	1·2
18 October 1960	33·46	34·74	34·56	0·76	− 0·32	22·36	21·74	35·0	9·1
29 November 1960	27·86	34·77	34·14	0·68	− 5·60	54·05	58·77	66·5	3·1
4 January 1961	29·86	34·76	33·80	5·87	+ 2·00	39·90	40·93	57·3	4·4
8 February 1961	29·87	34·88	33·69	4·11	+ 0·01	32·26	32·86	47·6	3·6
21 February 1961	32·84	34·66	33·61	3·38	+ 2·97	9·90	10·08	39·4	15·6
7 March 1961	32·90	34·58	33·57	0·37	+ 0·06	9·90	10·55	36·5	16·5
11 April 1961	31·68	34·10	33·34	0·44	− 1·22	15·56	14·84	22·9	3·5
25 April 1961	32·42	34·46	33·56	1·88	+ 0·74	3·68	3·23	13·6	4·2
9 May 1961	32·64	34·86	33·66	1·24	+ 0·22	3·68	3·56	13·6	4·1
25 May 1961	32·91	34·87	33·74	1·10	+ 0·27	3·82	2·47	12·3	3·3
12 June 1961	33·50	34·50	33·84	0·93	+ 0·59	2·83	1·83	8·1	5·7
31 October 1961	33·16	34·96							
28 November 1961	33·00	34·97	34·50	1·34	− 0·16	2·80	3·20	5·2	1·0
10 January 1962	33·10	34·82	34·20	1·20	+ 0·10	18·03	19·61	21·7	6·1

Table 7. —*continued*

Date	Salinity at power station S_n	Salinity at Galloper Lightvessel	Salinity assumed for coastal waters S_{sea}	$S_{sea}-S_o$	S_n-S_o	Total river flow 10^6m^3	Effective fresh water input to estuary 10^6m^3	River flow per tide 10^4m^3	Exchange coefficient (%)
17 January 1964	32·89	34·96	34·60	1·71	+ 0·69	1·45	1·19	5·3	2·9
30 January 1964	33·58	34·73	34·50	0·92	− 0·39	1·61	1·51	4·6	0·2
17 February 1964	33·19	34·82	34·40	1·21	− 0·29	0·95	1·14	4·5	0·2
28 February 1964	32·90	34·68	34·10	1·20	+ 0·15	9·23	10·95	28·1	9·2
16 March 1964	33·05	34·38	33·90	0·85	− 1·03	11·04	11·44	38·1	5·4
31 March 1964	32·02	35·10	34·00	1·98	+ 0·50	7·47	7·29	29·8	4·2
13 April 1964	32·02	34·99	33·90	1·88	− 0·34	8·04	8·58	25·9	3·7
29 April 1964	31·68	34·84	33·90	2·22	+ 0·19	3·20	2·31	11·8	1·3
13 May 1964	31·87	34·83	33·80	1·93	− 0·39	1·13	0·09	3·9	− 0·6
28 May 1964	31·48	34·82	33·70	2·22	+ 0·73	1·45	0·93	5·3	2·0
11 June 1964	32·21	34·70	33·70	1·49	+ 0·01	1·86	1·15	6·9	0·8
25 June 1964	32·22	34·67	33·70	1·48	+ 0·84	1·26	− 0·35	4·6	2·7
9 July 1964	33·06	34·63							

Before discussing the results of Method VI some comment is now needed on the determination of the various parameters in equations (2) and (3).

n — This is determined by taking the total duration of the period and dividing by 12 hours 24 minutes.

S_{sea} — This is the most difficult parameter to evaluate. For some of the periods values of salinity are available for coastal waters in the vicinity of the Spitway Buoy (Spencer 1964). In such cases a graph of the mean value of these measurements (at about high water) has been used in deciding the value to be taken for the sea salinity. Where this procedure was not possible sea salinity has been estimated with reference to the high-water salinity of the estuary and also to salinity measurements at the Galloper Lightvessel. It seems inevitable that where $(S_{sea} - S_o)$ is small (e.g. in the period 18 August to 15 September 1960) less significance can be attached to the calculated result for the exchange coefficient. On the other hand, where $S_{sea} - S_o$ is appreciable (11 to 25 April 1960, $S_{sea} - S_o = 1 \cdot 88$) a variation of as much as $\pm 0 \cdot 2$ in S_{sea} would cause an error of only $\pm 13\%$ (or $\pm 0 \cdot 4$) in the exchange coefficient. In the evaluation of the results of this method (Table 7) much must depend upon whether or not the assumed values of sea salinity can be accepted as reasonable.

r — This symbol represents the total quantity of fresh water entering the estuary as a result of river flow, direct rainfall over the surface of the estuary and evaporation. The need to include the latter two contributions was indicated by the fact that the river flow itself is, at some times of the year, very small. The method of estimating each of these contributions is now described separately.

(*i*) *River flow*

This estimate was based upon figures in the relevant issue of The Surface Water Year Book of Great Britain. The Year Book quotes mean monthly flows for the rivers and from these monthly figures the equivalent flow during the relevant part of the month was calculated by proportion. Since there was some reason to believe that there is a delay of a few days before flow, as measured at the gauging stations, is effective in the estuary, the period used for calculating river flow was four days earlier than the period for which the salinity values were to be used. The rivers flowing into the part of the estuary which is upstream from the power station and for which flows are quoted in the Year Book are the Blackwater, Chelmer and Ter. At times in summer abstractions for water supply purposes from these rivers may remove a large proportion of their total flow, the flow into the estuary then being very small. In these circumstances the flow of the Colne may be of the same order as that from the first three mentioned rivers. An examination of the freshwater budget at such times indicated that some fresh water from the Colne was finding its way into the upper part of the estuary. In an attempt to make some allowance for this it was assumed that 20% of the discharge from the Colne would enter the part of the estuary being considered. Before applying this correction the Colne flow itself was multiplied by $1 \cdot 62$ in order to allow for water from Roman River, and from Salary, Tenpenny, Sixpenny, St. Osyth and Bentley Brooks, which represent an additional catchment area of 15×10^7 m^2.

(*ii*) *Direct rainfall*

This contribution was calculated from weekly rainfall figures for Burnham-on-Crouch, together with the estimated surface area of the estuary which was taken as 3×10^7 sq. m.

(*iii*) *Evaporation from the surface of the estuary* was calculated using the formula:

$$E = (0{\cdot}26+0{\cdot}077V)(0{\cdot}98\, e_w - e_a)$$

where E = evaporation in mm cm^{-2} (24 hr)$^{-1}$

V = wind speed in m sec^{-1}

e_w = S.V.P. of water at the temperature of the water surface (mb)

e_a = partial pressure of water vapour in atmosphere (mb).

This formula for evaporation was suggested by Laevastu (1960). The values of wind speed and vapour pressure needed were obtained from the Daily Weather Reports of the British Meteorological Office and were for the nearest position to the Blackwater included in the Reports; for the period up to September 1961 this was Felixstowe, and subsequently Wattisham. In determining the value of e_w the temperature of the water was obtained from Central Electricity Generating Board records (Spencer 1964, 1965).

(*iv*) *Values of exchange coefficient derived using Method VI*

When it was decided to investigate this method it was realised that the error in individual results was likely to be quite high, but it was hoped that by taking a fairly large number of cases some useful indication of the value of the exchange coefficient would be obtained. The results are given in Table 7 and the following comments may be made:—

Most of the cases considered give results in agreement with the statement that during each tidal cycle between 1 and 5% of the high-water volume is lost from the estuary to the sea. Two cases where rather large values of exchange are predicted (March 1964 and September-October 1960) coincide with substantial increases in river flow. The negative exchange predicted for May 1964 is clearly misleading and this was a time of substantial fall of river flow. These three apparently anomalous results may, as mentioned above, be cases where the exchange formula fails because the distribution of fresh water in the estuary could change appreciably at times of rapidly varying river flow.

Two other cases where the predicted exchange is unexpectedly large or small are February 1964 and February-March 1961. On neither of these occasions do we find the period preceded by an appreciable change in river flow. It seems possible that in February 1964, when the flow of the Colne exceeded that from the Blackwater and the Chelmer, there was some change in the circulation in the estuary so that more fresh water accumulated near the mouth. Perhaps the biggest doubt is to be associated with the results for February-March 1961, when we find an unusually large exchange predicted. Unfortunately the salinity records for this period are especially difficult to interpret. The fact that salinity values as high as 36‰ are quoted on 8 March for water between the Spitway buoy and Clacton throws considerable doubt on the reliability of these figures.* This value is considerably in excess of that recorded at the Galloper Lightvessel on the following day. The salinity records also indicate a large variation; thus within half an hour the value seems to have dropped to 33·24‰. The unreliability of the offshore salinity records could be thought to throw doubt on the records for points within the estuary at this time, and it is possible that the prediction of a large exchange is an error produced by misleading salinity records. However, examination of the figures for estuarine salinity at this time fails to reveal any obvious discrepancy such as was found in the case of the offshore values. In the preceding months, river flow rates had been well above the level at which stratification begins to appear near the head of the estuary (Table 2), and the salinity records suggest that salinity gradients in the estuary had been increasing over this period. In March the records suggest that salinity gradients reached a maximum. A surface-bottom salinity difference of the order of 1‰ seems to have occurred at this time as far down the estuary as the power station, so that much of the estuary may have been vertically stratified. Over a period of four hours on the flood tide on 7 March the salinity near the power station increased by nearly 5‰, which is more than twice the total variation recorded after a comparatively large river flow in February 1962 (Survey C1).

* See comments by Spencer (1964) on possible error in the early records

After 7 March the records indicate greatly reduced salinity gradients. Whilst it is not possible to be certain, the evidence does suggest that conditions in the estuary in February 1961 were exceptional and there may have been an unusually large exchange of water with the sea at that time, as indicated by the exchange calculation. However, even if this large exchange did occur then, it is likely to recur only as a result of periods of unusually heavy rainfall, the river flows today being in general very much lower than they were in 1960-61 (Table 2).

DISCUSSION OF RESULTS FOR EXCHANGE OF WATER BETWEEN THE ESTUARY AND THE SEA

The work described has shown that the method proposed by Ketchum is not applicable to the Blackwater estuary. The idea of a coefficient of longitudinal eddy diffusivity has been found to be useful in describing the degree of longitudinal mixing within the estuary and with the sea. Calculated results for this coefficient suggest that mixing is most intense along the middle reach of the estuary. It has, however, been pointed out by the D.S.I.R. (Effects of Polluting Discharges on the Thames Estuary, 1964) that a simple differential equation cannot adequately represent mixing in an estuary, so that we should only use the idea of a coefficient of longitudinal eddy diffusivity where higher order differentials are likely to be small. Quantitative estimates of the degree of mixing with the sea suggest that between 1% and 5% of the high-water volume of the estuary is lost to the sea on each tide. This order of exchange was suggested by Parr's work based on the salinity data and is also consistent with later work using the total water budget, and the current and salinity measurements. Methods V and VI do not assume that a steady state of equilibrium has been reached between the estuary and the sea, as do all the other approaches considered. It should perhaps be pointed out that the water budget method (Method VI) should give the same results as that used by Parr and based on salinity data (Method II), if the salinity of the estuary is steady (Appendix II). Operations 3 and 5 were carried out at times when the salinity of the estuary was not changing rapidly, and the agreement between Parr's results and those of the water budget method is therefore to be expected.

RESULTS OF OTHER WORK CARRIED OUT IN THE BLACKWATER

In addition to the work of the main hydrographic surveys, which has already been described, two other types of experiment have yielded useful information regarding water movements in the estuary. The first of these made use of the bacterium *Serratia* (Rippon, White and Wood 1961; Rippon 1962) and the second involved the release of Woodhead sea-bed drifters.

In the experiments using *Serratia* a volume of approximately 40 litres of a broth culture containing some 10^{13} *Serratia* cells was released at a predetermined state of the tide. The results of these experiments indicated that initial dispersion of the *Serratia* was rapid, so that within a small number of tidal cycles almost all the water in the estuary contained detectable numbers of cells. After this rapid initial effect subsequent dispersion was slow and the total decrease in the population of *Serratia* cells in the estuary was comparable with that to be expected from their rate of mortality (50-70% in 24 hours).

In order to obtain information concerning vertical mixing, samples were taken at the surface, mid-depth and near the bottom. No significant variation with depth has been reported, this being consistent with the lack of vertical stratification that was revealed by the hydrographic surveys. The fact that *Serratia* cells were moved from one side of the estuary to the other in a small number of tidal cycles indicates a significant degree of transverse mixing.

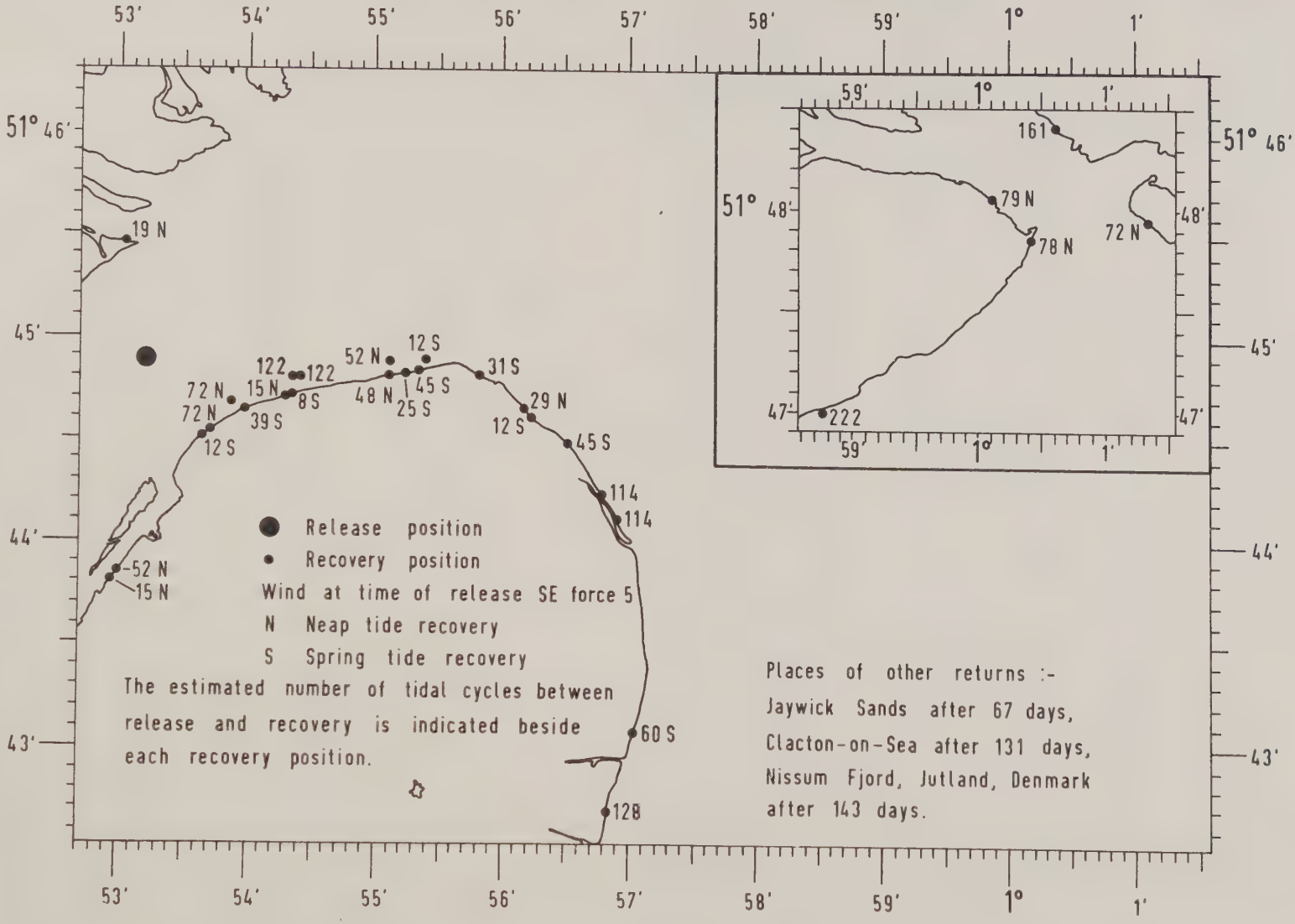
The results of the sea-bed drifter experiments are described in rather more detail, since these have not been published separately. The releases were made on 29 September and 8 and 11 October 1960, the September releases being from a position at approximately mid-stream opposite the power station and close to the release point for the *Serratia* experiments (Figures 42-44). In October the releases were from a position further offshore, near to the Bench Head Buoy (Figures 45-47). At each position fifty drifters were released at each of three states of the tide: high water, middle ebb and low water respectively. As might be expected from releases made so close inshore, return rates of the drifters were high (Table 8).

Table 8. *Numbers of Woodhead sea-bed drifters returned within 33 days*

Release point	State of tide at release		
	High water	Middle ebb	Low water
Power station transect	23	29	35
Bench Head buoy	10	25	20

(Each release consisted of 50 drifters)

Fig. 42. *Returns of Woodhead sea-bed drifters released from the power station transect at high water on 29 September 1960.*



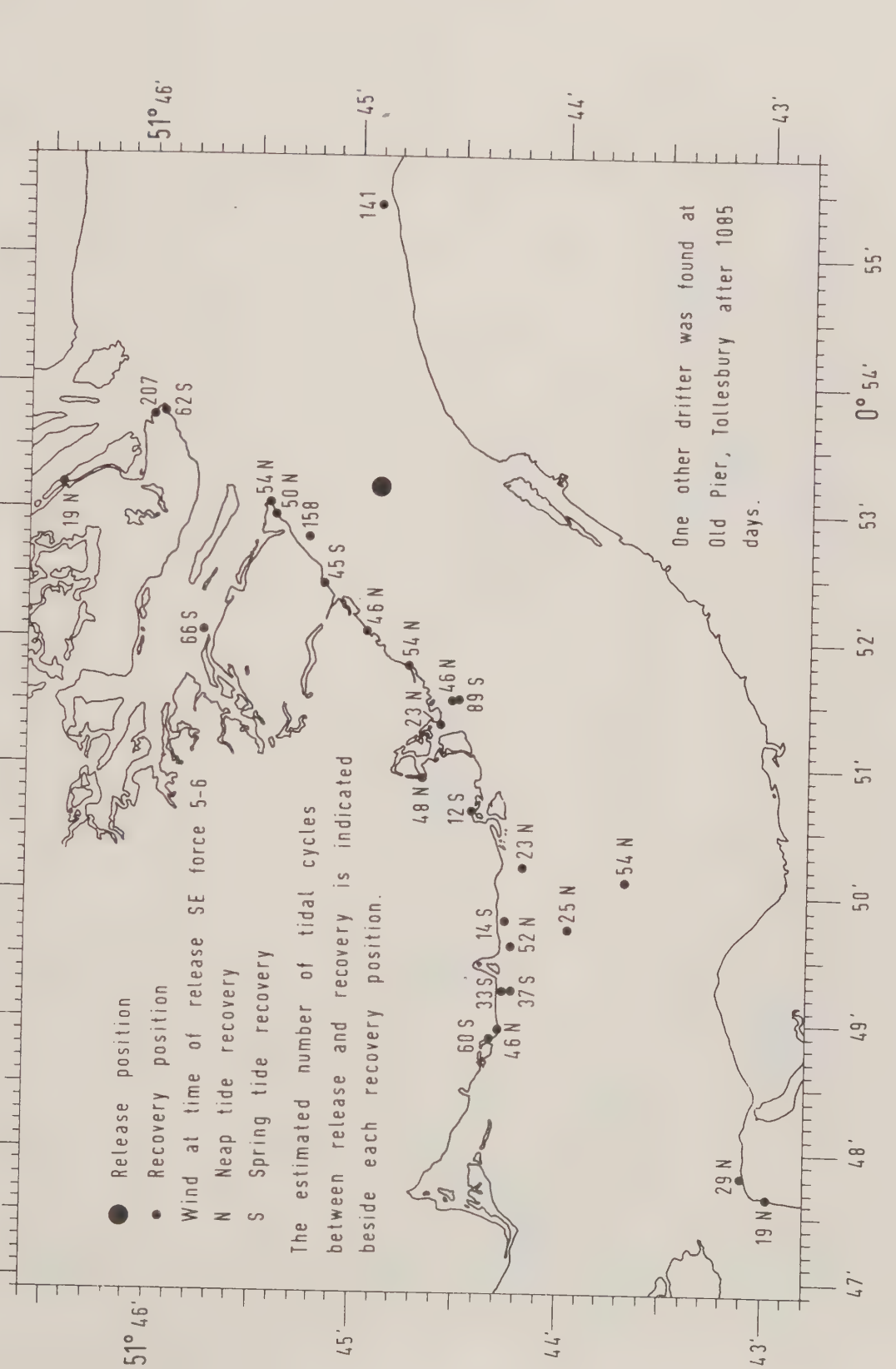
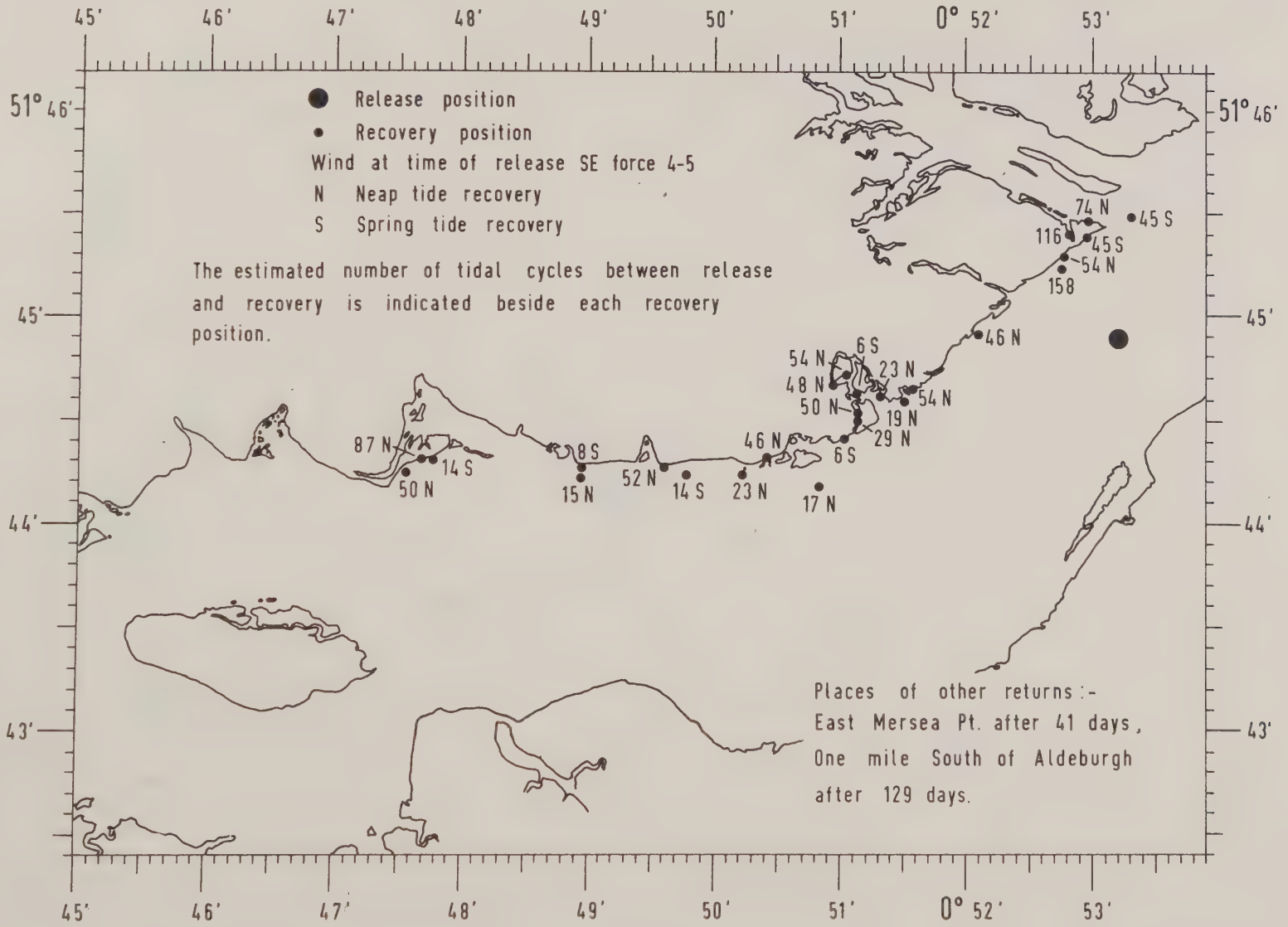


Fig. 43. *Returns of Woodhead sea-bed drifters released from the power station transect at middle ebb on 29 September 1960.*

Fig. 44. *Returns of Woodhead sea-bed drifters released from the power station transect at low water ou 29 September* 1960.



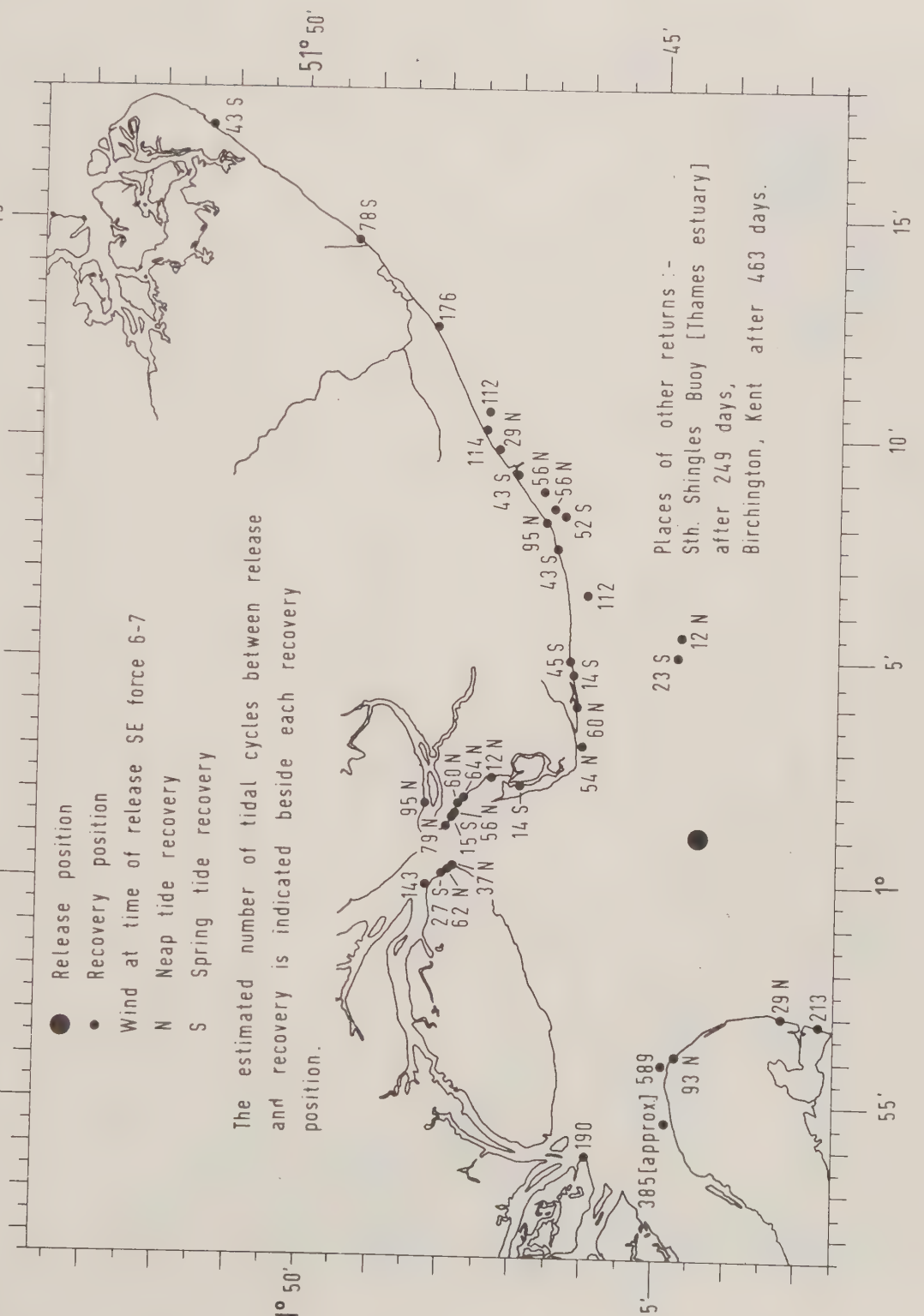
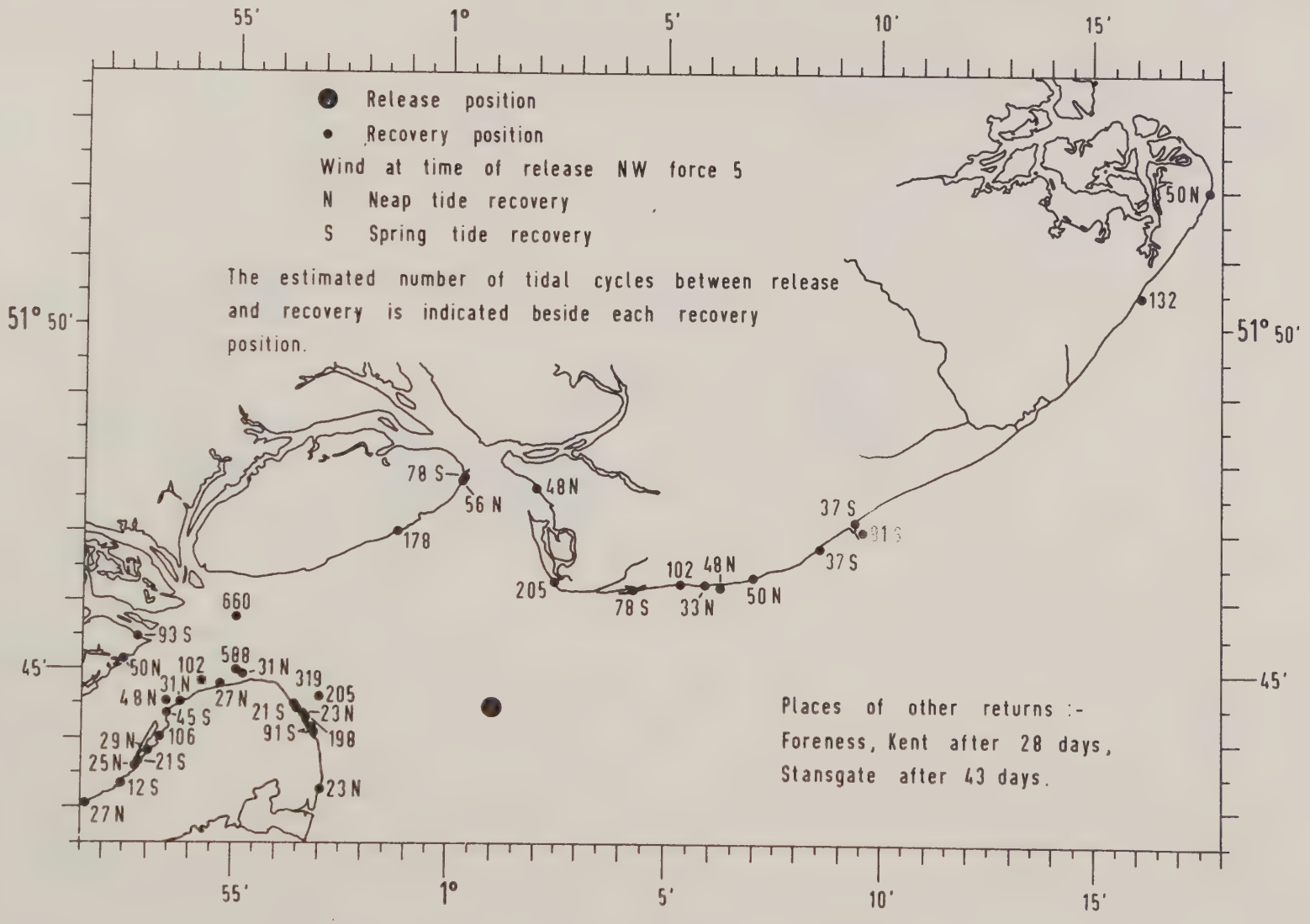


Fig. 45. *Returns of Woodhead sea-bed drifters released from the Bench Head buoy release at high water on 8 October 1960.*

Fig. 46. *Returns of Woodhead sea-bed drifters from the Bench Head buoy release at middle ebb on* 11 *October* 1960.



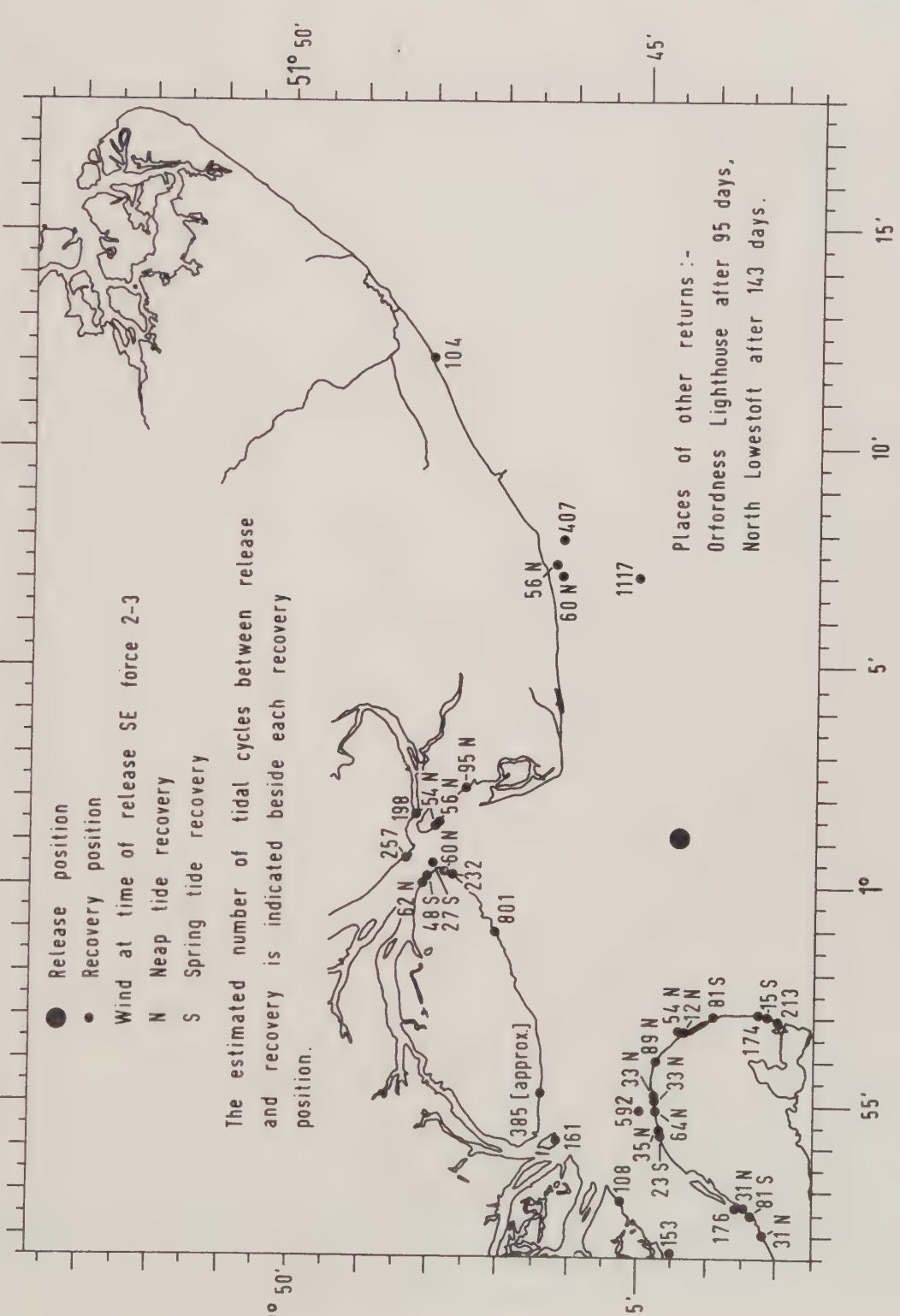


Fig. 47. *Returns of Woodhead sea-bed drifters released from the Bench Head buoy at low water on 8 October 1960.*

The following comments refer to the returns within 33 days of release, because markers were returned at a steady rate up to that time. Returns after 33 days were few and irregular, and it was felt that the inclusion of these late results was unlikely to be helpful in the establishment of the water movements in the estuary.

The reported positions of the returns from the various releases are shown in Figures 42-47 and it is immediately apparent that there is a marked connection between the phase of the tide at which the release was made and the point of recapture of the drifter. Thus, with only one exception, all returns from the first batch, released at high water, were found on the southern shore, whereas all of those released at low water, and all but one of the middle ebb releases, were recovered from the northern shore. This feature is remarkable, particularly in view of the length of time the drifters are believed to have been in the water. A second feature of these results is that, of the drifters stranding on the northern shore, the majority were found at times of neap tides, but no such tendency was found for those recaptured on the southern shore, which came in steadily throughout the period. Whilst the slow movement of these drifters to the shore must be related to the residual water movements within the estuary, the precise interpretation of this feature of the results appears to be difficult. The dependence of the point of return upon the time of release in this experiment indicates a low degree of longitudinal mixing in the estuary. It is remarkable that, even after fifty tidal cycles, the point of return of the drifters should show such a marked dependence on the phase of tide at which the release was made. The effect of releasing at different phases of the tide is the same as would have been achieved if the releases had been made simultaneously but at different positions, spaced along the length of the estuary. From the distribution of the points of return we must conclude that very little intermixing took place between the three releases of drifters from each position.

This last conclusion is in contrast with the degree of homogeneity revealed by the hydrographic surveys and by the results of the *Serratia* experiments. It must, however, be remembered that the experiments with sea-bed drifters and those with *Serratia* involve fundamentally different types of measurement. The latter should follow and be affected by all water movements, whereas the drifters are designed to remain on the sea bed and so should not respond to vertical water movements. It would therefore appear that the vertical mixing of the water may play an important part in the process leading to the large degree of longitudinal dispersion observed in the Blackwater. This vertical mixing, together with the decrease of the amplitude of the tidal excursion with depth, could produce a considerable degree of longitudinal mixing. If this explanation is correct the longitudinal mixing is related to the vertical current shear observed on flood tides which results from the tendency for surface waters to flow on to the mud flats. This would be consistent with the fact that the deduced values for the coefficient of longitudinal eddy diffusion indicate a maximum value within the estuary (Table 12, Appendix III). In order to illustrate the part that vertical current shear could play in the longitudinal mixing process, Table 9 shows values of $\int$ udt over both ebb and flood halves of the tidal cycle at proportional depths of 0·1 and 0·9. These results, which are for the three most seaward positions of the longitudinal surveys (Positions III, IV and V, Figure 2), show that the total water excursion near the surface is considerably larger than that near the bottom, both on flood and ebb, and that if strong vertical mixing is to be expected the vertical current shear could easily lead to longitudinal dispersion of the magnitude recorded in the experiment using *Serratia*.

Although the returns of drifters from the more offshore release do show that the time of release, relative to the tidal cycle, is important, the correlation between point of return and time of release is not quite so great as for the inshore releases. It is, however, noticeable that drifters from the low-water release at the offshore position move mostly to the Bradwell-St. Peter's Flats area, whilst 90% of the returns from the high-water release were found to the north-east, along the Essex coast. A few returns of drifters that had been at sea for more than 33 days were from parts of the coast some distance from the Blackwater, the most northerly return reported being from the October low-water release. This drifter was washed ashore at Lowestoft after an estimated time at sea of 143 days.

Table 9. *Total water excursion* ($\int udt$, *in km*) *indicated by current meter readings during Operations* 3 *and* 5

Survey	Proportional depth	*TELLINA* Position V		*WYSTRYS* Position IV		*JASSA* Position III	
		ebb	flood	ebb	flood	ebb	flood
A1	0·1	10·0	12·1	11·5	12·1	15·3	14·6
	0·9	6·3	6·6	6·5	9·1	11·2	9·5
A2	0·1	8·0	9·1	10·0	7·3	12·0	11·3
	0·9	6·3	5·7	6·7	4·6	7·3	9·0
C1	0·1	13·1	10·8	12·4	9·8	11·8	11·0
	0·9	8·4	8·5	8·4	7·6	8·4	8·3
C2	0·1	8·8	7·7	9·4	7·9	8·7	9·8
	0·9	6·2	5·9	6·1	5·1	5·1	7·3

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I have also used information supplied by the Essex River Authority and by the Central Electricity Generating Board, to whom my thanks are due. For the loan of gear and instruments I am grateful to: the Department of Oceanography, University of Liverpool; the Hydraulics Research Establishment, Wallingford; the National Institute of Oceanography; Kelvin-Hughes Instruments Division, and the Hydrographic Department of the Ministry of Defence.

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APPENDIX I
HYDRODYNAMICS OF FLOW ON TO A MUD-FLAT AREA

In this appendix an attempt is made to calculate the velocity distribution when a uniform stream flowing over a smooth bottom reaches a region of decreasing depth of the form indicated in Figure 48.

Two-dimensional flow is assumed, the lines of flow being confined to the plane of the lines of maximum slope of the rise in the bottom. Effects associated with the sides of the channel are ignored and the flow is assumed to be irrotational and unaffected by viscosity.

Using the complex notation we may consider this idealized situation to be represented by two sources of strength m at points (0, ia) and (0, $-$ia) in the complex plane (x + iy), together with a uniform stream of strength U parallel to the x axis.

The complex potential representative of this flow will be

$$w = -Uz - m \log (z - ia) - m \log (z + ia) \tag{1}$$

where $z = x + yi$

and $w = \varphi + i\psi.$ (2)

In equation (2)

φ = velocity potential

ψ = stream function.

The complex velocity will be given by:

$$-\frac{dw}{dz} = u - iv;$$

thus, differentiating equation (1) and then equating real parts gives

$$u = U + \frac{2mx(x^2 + y^2 + a^2)}{(x^2 - y^2 + a^2) + 4x^2y^2}. \tag{3}$$

This equation represents the horizontal component of the velocity and it is this that is required, since the Direct Reading Current Meters used in the surveys will have given values for this velocity component.

In order to apply equation (3) to a particular problem it is necessary to relate the various constants that have been introduced, and to derive an equation for the shape of the bottom topography.

It follows from equation (1) that the stream function, ψ, is given by

$$\psi = -Uy - m \tan^{-1} \frac{y - a}{x} - m \tan^{-1} \frac{y + a}{x}$$

which, on rearrangement, gives

$$x^2 - y^2 + a^2 + 2xy \cot \left(h\frac{y}{a} + k \right) = 0.$$

or, writing $\frac{Ua}{m} = h$

and $\frac{\psi}{m} = k$

$$x^2 - y^2 + a^2 + 2xy \cot \left(h\frac{y}{a} + k \right) = 0.$$

We may choose $h = 2$

and $k = 0{\cdot}6$

as suitable values for these constants to give a reasonable form for the shape of the bottom topography.

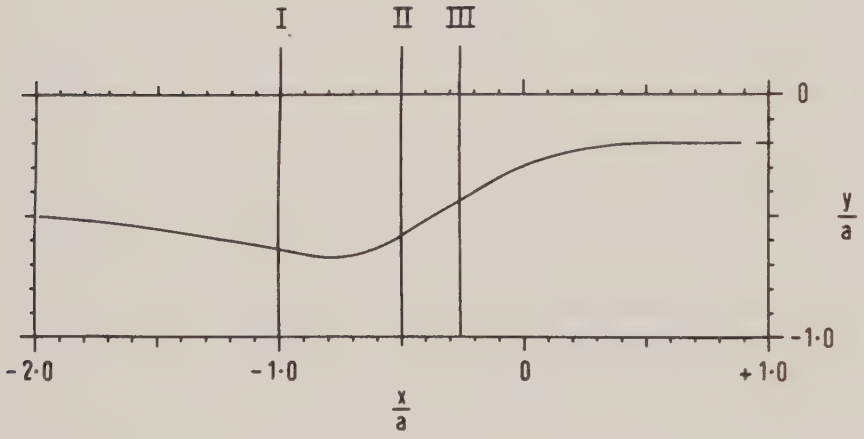
The equation for the bottom of the stream is thus:

$$x^2 - y^2 + a^2 + 2xy \cot \left(2\frac{y}{a} + 0{\cdot}6 \right) = 0 \tag{4}$$

which is plotted in Figure 48.

Equation (3) has been evaluated for positions along the three lines I, II and III in Figure 48, and the velocity variation that is predicted is shown in Figure 29 (ii). The line $y = 0$ has been taken to represent the surface of the water and it is certainly a streamline for the case considered. In order that this streamline may be regarded as the surface of the water it should also be a line of constant pressure. This is not precisely the case, but, for the magnitude of velocity measured at positions near the flats (< 100 cm/sec), an application of Bernoulli's equation shows that the variation of pressure along this streamline is quite small and corresponds to a head of water of only approximately 10 cm.

Fig. 48. *Variation of depth adjacent to mud flats that is considered in the theoretical calculation of velocity distribution (Appendix I).*



APPENDIX II
COMPARISON OF METHODS II AND VI FOR ESTIMATING EXCHANGE OF WATER BETWEEN THE ESTUARY AND THE SEA

In the working of Method II it is assumed that a volume of water (ΔV) must escape from the estuary on each tide such that:

$$\Delta V = \frac{R}{f}$$

where R = river flow per tide

and f = fraction of the estuarine water, at the mouth of the estuary, that is fresh.

In terms of the fraction (ε) of the high-water volume (V) that is lost, we have

$$\varepsilon V = \frac{R}{f}$$

$$\text{or } \varepsilon = \frac{R}{V} \frac{S_{sea}}{S_{sea} - S_{est}}. \tag{1}$$

In method VI we have used

$$\varepsilon = \frac{1}{n\,(S_{sea} - S_o)} \left[S_n - S_o + \frac{nr}{V} S_o \right].$$

For steady conditions $S_n = S_o = S_{est}$

and

$$\varepsilon = \frac{r}{V} \frac{S_{est}}{S_{sea} - S_{est}}. \tag{2}$$

Thus, under steady conditions, the equations representing these methods differ in two respects:

(i) Method II uses river flow (R), whereas Method VI uses total freshwater input (r).

At the time of Operation 5 the main contribution to the freshwater input was the river flow and so, for this operation, we should expect little difference to arise from this factor. During Operation 3 factors other than river flow may have made appreciable contributions to the total freshwater input, and in this case the deductions from this Method may therefore be misleading.

(ii) Method II involves S_{sea} in the numerator instead of S_{est}.

This difference is negligible when considering the accuracy that is likely to be obtained in evaluating the exchange factor.

APPENDIX III
THE BLACKWATER ESTUARY: SOME ESTIMATES OF MIXING AND FLUSHING RATES

G. B. Parr

Formerly at the Fisheries Laboratory, Lowestoft and now at Skipton Grammar School

The operation of the Bradwell nuclear power station may involve the abstraction from the estuary of water for cooling purposes at rates of up to 20 million gallons per hour. This water, after passing through the generator cooling system, will have risen in temperature by about 8°C. and the warmed water is then returned to the estuary. A consideration of whether such quantities of heat can be released into the estuary without detrimental effect on the marine life leads to questions involving two features of the movement of the estuarine waters.

In the first place it is desirable that there should be a high degree of mixing within the estuary in order to prevent the concentration of heat at any place removed from the barrier wall region. Given that this dispersal is satisfactory the estuary will act as a cooling pond and some of the heat introduced will be lost from the surface to the atmosphere. A second process which might involve the loss from the estuary of appreciable quantities of heat is the exchange of estuarine water with the sea.

It is a general conclusion from the hydrographic work that has been carried out that there is a considerable degree of mixing of water within the estuary and the following discussion therefore considers the second process, that of exchange with the sea.

The main channel of communication between the estuary and the North Sea is formed by the Wallet and an investigation of the salinity distribution in this region was carried out on 4 March 1962, when 34 offshore stations were worked from east to west, those in the mouth of the estuary being worked at high water. The positions of these stations are shown in Figure 49, together with the surface isohalines deduced from this survey. This surface salinity distribution is consistent with the results of a more thorough survey of the area, carried out two years later (Appendix IV). Near the mouth of the estuary we see a configuration of isohalines suggestive of an outflow of estuarine water, but there appears to be no particular line of demarcation between the water of the estuary and the sea. This was as expected and it shows that any choice of position for the limit of the estuary and the start of the sea is necessarily an arbitrary one. Since we are here interested in the power station we will take the position of that as the limit of the estuary for our considerations. By doing this we will cover only that part of the estuary which has been surveyed along its length. We will also avoid bringing into the estuary system the West Mersea creek complex and the River Colne, about which we know little, and the exchange and mixing characteristics will refer to that body of water upstream from the power station, where any warm effluent is likely to have most effect.

Taking the power station as being at the mouth of the estuary, and taking the head of the estuary to be at Beeleigh Grange Lock, the volumes of water within the estuary at high and low waters of spring and neap tides have been calculated, and the tidal prism volume (equal to high-water volume minus low-water volume) compared with the summer river flow per tide, R (Table 10).

The values of the river run-off during the surveys were:

(a) Spring tide (i) Summer (Survey A1) $2{\cdot}2 \times 10^4$ m^3/tide
(ii) Winter (Survey C1) $7{\cdot}3 \times 10^4$ m^3/tide
(b) Neap tide (i) Summer (Survey A2) $2{\cdot}6 \times 10^4$ m^3/tide
(ii) Winter (Survey C2) $6{\cdot}4 \times 10^4$ m^3/tide.

It can thus be seen that the tidal prism volume is a large fraction of the high-water volume, and that it is very large compared with the river flow per tide.

Fig. 49. *Distribution of salinity* ($^0/_{00}$) *in the Wallet*, 4 *March* 1962.

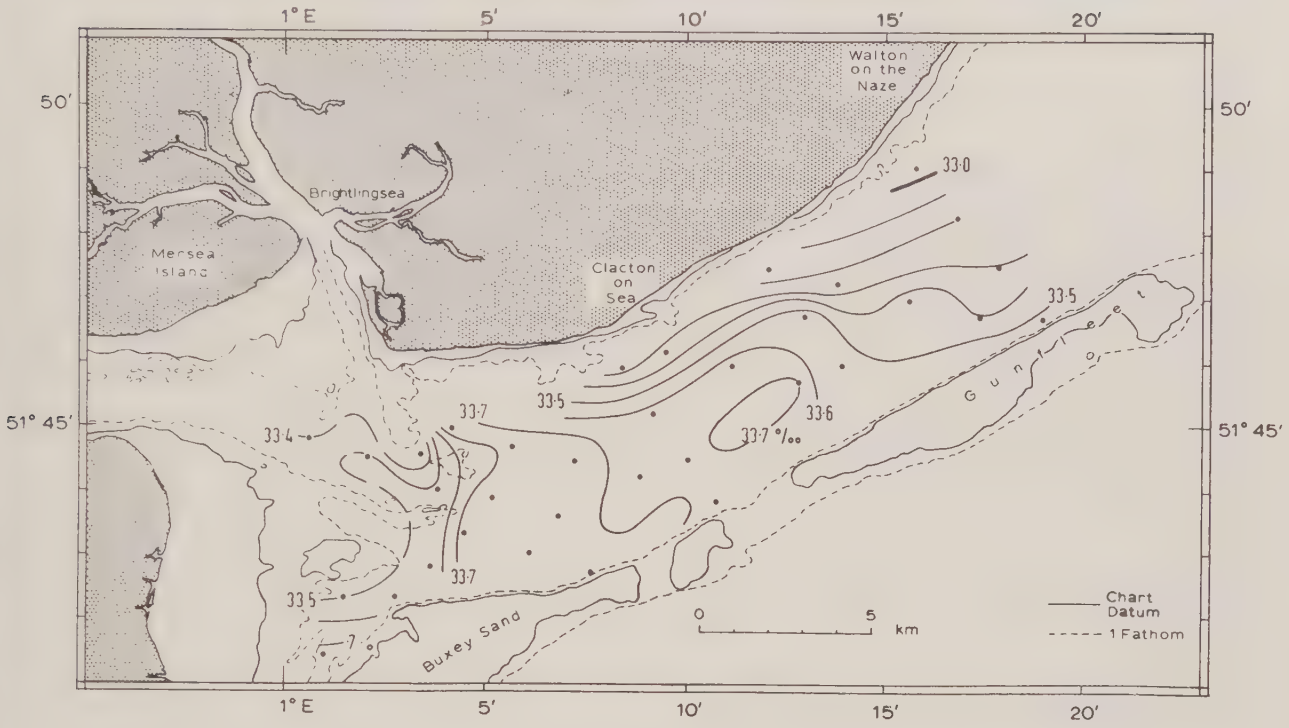


Table 10. *Typical values of tidal flow past the power station, compared with the summer river flow per tide*

	Volumes (10^6 m^3)		$\frac{V - v}{R}$
	High water (V)	Low water (v)	
Spring tide	137	40·5	4400
Neap tide	110	51·5	2250

The four approaches to the question of exchange of estuarine water with the sea that were investigated have been referred to above as Methods I-IV. These methods are now discussed in more detail.

METHOD I
CONSIDERATION OF KETCHUM'S SEGMENTATION METHOD

This method (Ketchum 1951*a* and *b*) has had considerable success when applied to various bays and estuaries in the United States and Canada. In his approach, Ketchum used a modified tidal prism theory such that the estuary or bay is segmented so that the low-tide volume of any one segment v_n is equal to the high-tide volume of the adjacent landward segment, $V_{(n-1)}$. The head of the estuary, for the purpose of this segmentation process, is where the tidal prism volume is equal to the river flow per tide, so that at high tide the first segment is full of fresh water. By segmenting the estuary in this way a piston effect of the water entering on the flood tide is envisaged, so that the length of a segment is equal to the average excursion of a particle of water on the flood tide for that part of the estuary. On an ebb tide each segment (n) loses a proportion of its volume to the (n + 1)th segment. This proportion will be given by

$$r_n = \frac{V_n - v_n}{V_n}.$$

By summing the water of various ages (in tidal cycles) within the nth segment, Ketchum shows that the concentration of river water in this segment is

$$Q_n = \frac{R}{r_n}.$$

Also the flushing time for any one segment is

$$t_F = \frac{Q_n}{R} = \frac{1}{r_n}.$$

Using this theory, the following parameters have been computed for the Blackwater estuary:

t_F = flushing time in tidal cycles beyond each station in turn, time zero being at the station which is furthest landward
Q = volume of fresh water between stations
P = volume of mixed water escaping beyond the given station at each ebb tide.

The results of this work are shown in Table 11.

METHOD II
USING OBSERVATIONS OF SALINITY WITHIN THE ESTUARY

If S_d is the salinity of the water at some point within the estuary at a given time, and S is the salinityof the water before dilution, then, if salinity can be taken as a tracer of water types, the fraction of fresh water present is given by

$$F_f = \frac{S - S_d}{S}$$

S_d is taken as the salinity at high water, that is just before the onset of an ebb tide, and S is taken,where possible, as the salinity just offshore from the Essex coast at the mouth of the estuary. For each of the five stations in Surveys A and C we have two values of S_d which are depth mean values at each of two high waters. If we assume that the mean salinity for any cross-section is given by the depth mean value in the the middle of the channel, then from these values of S_d we can deduce the mean high-water salinity of each segment of the estuary for each survey. Knowing the value of S, the value of F_f for each segment of

Table 11. *Comparison of the parameters for the segmented estuary as predicted by the method of Ketchum* (1951 *a and b*) *and as deduced from the results of the hydrographic surveys*

Station	Distance from Beeleigh Grange Lock (km)	Distance from first station (km)	Spring tide						Neap tide					
			Predicted values (Method I)			Survey results (Method II)			Predicted values (Method I)			Survey results (Method II)		
			t_F (tidal cycles)	Q (10^4 m^3)	P (Volume lost per tide) (10^4 m^3)	t_F (tidal cycles)	Q (10^4 m^3)	$\frac{R}{\overline{F_t}}$ (Volume lost per tide) (10^4 m^3)	t_F (tidal cycles)	Q (10^4 m^3)	P (Volume lost per tide) (10^4 m^3)	t_F (tidal cycles)	Q (10^4 m^3)	$\frac{R}{\overline{F_t}}$ (Volume lost per tide) (10^4 m^3)
			SUMMER (Surveys A1 and A2)											
EVELYN	8·69	0	0	0	1450	0	0		0	0	650	0	0	
MERSEA LASS	11·89	3·20	0·4	1·4	3330	16·1	35·3	169	1·2	3·0	149	3·5	9·3	303
JASSA	14·42	5·73	1·1	2·5	4640	25·5	57·1	244	2·2	5·6	2000	9·5	24·9	329
WYSTRYS	17·03	8·34	1·7	3·8	5130	40·2	88·6	244	3·5	8·9	2270	17·8	46·7	376
TELLINA	19·41	10·72	2·2	4·9	5860	50·2	110·1	275	4·7	12·2	2520	25·4	66·6	376
			WINTER (Surveys C1 and C2)											
SALLIE	8·69	0	0	0	1350	0	0		0	0	640	0	0	
CLUARAN	11·89	3·20	0·6	4·3	3160	23·9	173·8	117	1·2	7·6	1650	17·8	114·5	115
JASSA	14·42	5·73	1·1	7·6	4640	36·0	261·5	196	2·2	14·4	2040	26·8	172·3	208
WYSTRYS	17·03	8·34	1·7	11·6	5730	48·4	351·3	290	3·3	21·8	2350	36·6	235·7	322
TELLINA	19·41	10·72	2·2	15·9	6300	53·9	391·6	454	4·6	29·6	2410	42·8	275·5	460

estuary between the stations can be worked out. By assuming that the inflow of fresh water at the head of the river takes place at a rate which is constant over the period of the survey and is equal to the mean rate of flow over this period (R), and that the water within the estuary does not become more or less saline over an integral number of tides, the volume of water lost beyond each station on each ebb tide is R/F_f

Knowing F_f and the high-water volume V for any segment, the accumulation of river water within that segment is F_fV. Then, accepting the above rates of river flow, the flushing time between the stations at the ends of the segment is $(F_fV)/R$ tidal cycles. These parameters have been calculated for the estuary, using the data of Surveys A1, A2, C1 and C2.

Table 11 shows the results of this work, the omission of values of R/F_f for the first station in this table arising from the fact that no salinity data were available for the region of the estuary above this station. Also, for the calculation of F_f for Survey A, the Galloper Lightvessel value of S was used, whilst for Survey C the value was that offshore from the mouth of the estuary. This procedure results in too high a value of F_f for Survey A, so that Q is too high, t_F is too high and P is too low.

A comparison of the results of Methods I and II, as shown in Table 11, reveals a considerable discrepancy between them; the first was based on Ketchum's segmentation theory and the second upon survey results. A similar discrepancy between the predictions of Ketchum's theory and survey measurements was found by Stommel and Farmer (Stommel 1953) when considering the Severn estuary.

METHOD III
CALCULATION OF LONGITUDINAL EDDY DIFFUSION COEFFICIENTS

In order to compare the amount of mixing taking place within various estuaries of the British Isles, Bowden (1963) has produced a simple equation for the effective longitudinal coefficients of eddy diffusivity, K_x, and in order that the Blackwater estuary may be compared with the tabulated values given by Bowden, the same equation is used here. The equation takes the form

$$K_x = \frac{r\,\bar{S}}{A\,\dfrac{\delta\bar{S}}{\delta x}}$$

where r = river flow in $cm^3\ sec^{-1}$,
$\bar{S}$ = mean salinity over a whole number of tidal cycles,
A = area of cross-section of estuary channel,
x = distance measured in the seaward direction along the length of the estuary,
and K_x = the effective value of the eddy diffusitivity at the point in question.

All of these variables are at hand for Surveys A and C. Table 12 shows the results of this work and also similar results reported by Bowden (1963) for the Thames estuary.

METHOD IV
CONSIDERATION OF THE EFFECT OF BOTTOM FRICTION

The results of an alternative approach have been included in Table 12. This method also was considered by Bowden (1963) who extended a semi-empirical formula for pipes and open channels (Taylor 1954 and Elder 1959) to the case of oscillatory flow in channels. In this way a formula was produced for the coefficient of eddy diffusivity, on the assumption that the mixing process was caused by the frictional effects of the sides of the channel. This equation is

$$k_x = 0{\cdot}15\ Uh$$

where U = tidal current amplitude
and h = depth of channel.

These coefficients are given in Table 12 for Operations 3 and 5, at various positions within the estuary.

The column containing ΔS shows the mean value of the surface-bottom salinity difference over a tidal cycle as an indication of the degree of vertical homogeneity of the estuary. The values of the coefficient K_x for the various positions within the estuary show that the eddy diffusion is low both towards Osea Island and towards the power station. On three out of the four surveys the maximum value occurred in the Stone region, which would thus appear to be a region of comparative instability as regards flow characteristics. The value of the coefficient k_x increases towards the mouth of the estuary and the two

Table 12. *Coefficients of horizontal eddy diffusitivity calculated from the results of Operations* 3 *and* 5 *in the Blackwater and compared with results quoted by Bowden for the Thames estuary*

Estuary and Survey	Position in estuary	ΔS (°/₀₀)	K_x (10^5 cm^2 sec^{-1})	k_x (10^5 cm^2 sec^{-1})
Blackwater	West Osea Island	0·08	0·60	0·04
Survey A1	East Osea Island	0·02	3·80	0·09
Summer,	The Stone	0·02	4·00	0·13
spring tide	Mill Creek	0·00	2·70	0·13
	Bradwell N.P.S.	0·00	4·50	0·16
Blackwater	West Osea Island	0·08	1·50	0·03
Survey A2	East Osea Island	0·03	4·80	0·07
Summer,	The Stone	0·05	7·00	0·10
neap tide	Mill Creek	0·02	2·70	0·09
	Bradwell N.P.S.	0·00	2·50	0·14
Blackwater	West Osea Island	0·76	1·30	0·04
Survey C1	East Osea Island	0·11	2·70	0·10
Winter,	The Stone	0·13	4·30	0·13
spring tide	Mill Creek	0·12	4·30	0·15
	Bradwell N.P.S.	0·13	1·20	0·20
Blackwater	West Osea Island	0·69	1·10	0·03
Survey C2	East Osea Island	0·14	3·40	0·06
Winter,	The Stone	0·15	4·20	0·08
neap tide	Mill Creek	0·11	2·50	0·11
	Bradwell N.P.S.	0·09	1·10	0·12
Thames (low	10 miles below London Bridge	1·00	5·30	0·17
river flow)	25 miles below London Bridge	1·00	8·40	0·24

sets of spring tide values agree closely with each other, as do the two sets of neap tide values. The coefficient k_x is generally a few parts per hundred of the coefficient K_x, but at the *TELLINA* position near the power station (Station V, Figure 2), during Survey C1, it did reach one-sixth of K_x. It can be seen, however, that the friction effect is a minor contribution to the eddy diffusivity.

CONCLUSIONS

It appears that, according to the tidal situation and the land run-off, it takes between 12 and 27 days approximately to flush the fresh water through the 11 kilometres from Osea Island to the Bradwell nuclear power station, and that at the power station between one part in 50 and one part in 24 of the high-water volume of the estuary is lost during each tidal cycle. Considering this and the high degree of mixing within the estuary, any hot water from the power station released into the estuary at the barrier wall can be expected to disperse very quickly.

APPENDIX IV
SURFACE SALINITY CONDITIONS IN THE WALLET, 1-10 APRIL 1964

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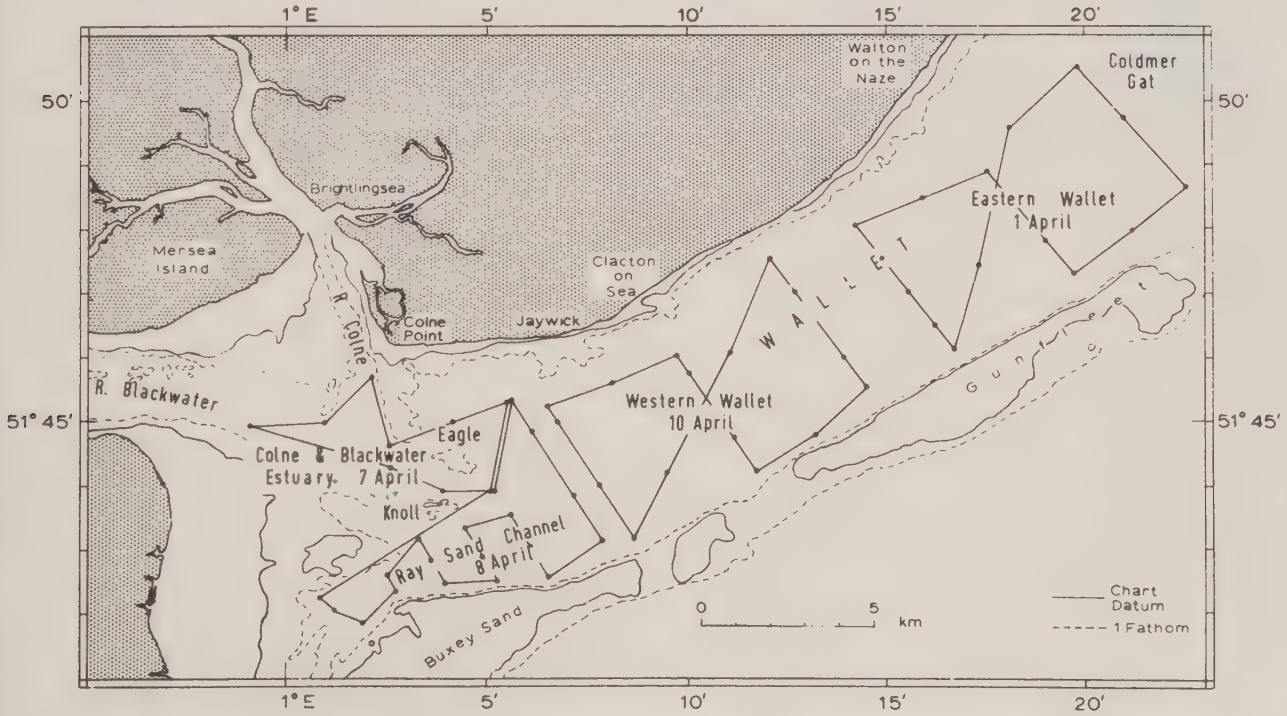
INTRODUCTION

A survey of the Wallet, the roadstead bounded by the Gunfleet and Buxey Sands to the south-eastward and by the coast between Walton-on-the-Naze and Colne Point to the north-westward, was carried out in early April 1964 by Mr. J. W. Ramster from R.V.s *PLATESSA* (1 April) and *TELLINA* (7-10 April). The area was covered in four stages, each stage occupying one day of the survey. Each ship steamed around a grid of as many stations as could be conveniently worked in about two hours and then immediately commenced another circuit of the grid, until a series of observations had been obtained at each of the stations over the major part of a tidal cycle. The four station grids are shown in Figure 50.

The surface salinity observations at each of the stations have been plotted against time, each day's survey being referred to the predicted times of high and low waters at Clacton. Linear interpolations between the observed values have allowed Figures 51 to 56 to be drawn, representing the isohalines at two-hourly intervals during the course of a tide. Many local variations must have occurred during the ten days spanned by the survey and it has not been possible to take these into account. Nevertheless, the figures show a coherent sequence of events taking place in the Wallet, and discussion of the figures is followed by details of such deviations as were observed. These figures are based upon Admiralty Chart No. 1975, and show the Buxey Gunfleet sand banks as rather more prominent than they are today.

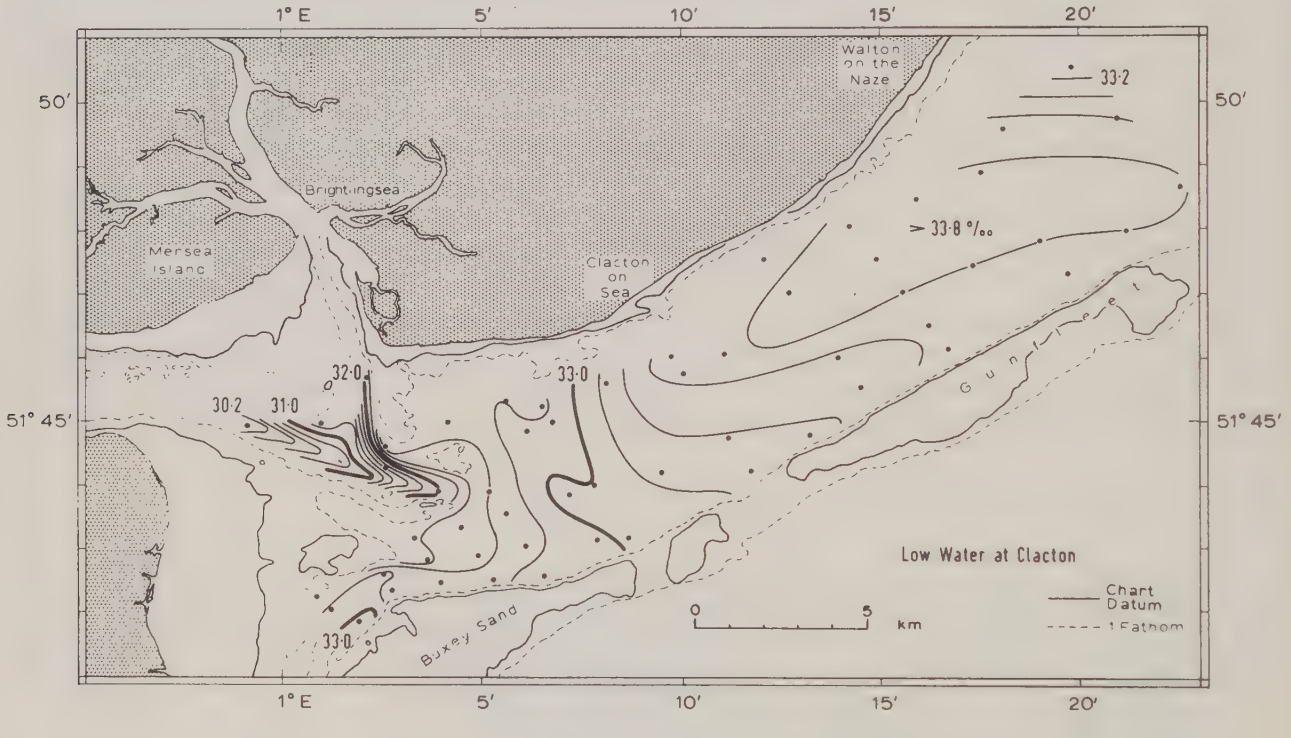
Fig. 50. *The four station grids that were surveyed in the Wallet in April* 1964.



1. *Low water at Clacton* (*Figure* 51)

This figure shows the largest range of salinity values found in the area. Water of salinity slightly above $33{\cdot}8^0/_{00}$ is found in the eastern Wallet, centred to the south of Walton-on-the-Naze, and water of salinity less than $30{\cdot}2^0/_{00}$ is present at the station in the lower reaches of the River Blackwater. The outflow of the Blackwater and Colne rivers is well marked in the channel between the Knoll and Eagle banks. The $33^0/_{00}$ isohaline runs roughly due south from the coast at Jaywick, and appears again in the Ray Sand Channel, where a small tongue of more saline water is to be found. The picture as a whole suggests that the main outflow of the estuarine water is taking place on the south-eastern side of the Wallet, the salinity decreasing as one moves offshore from Clacton.

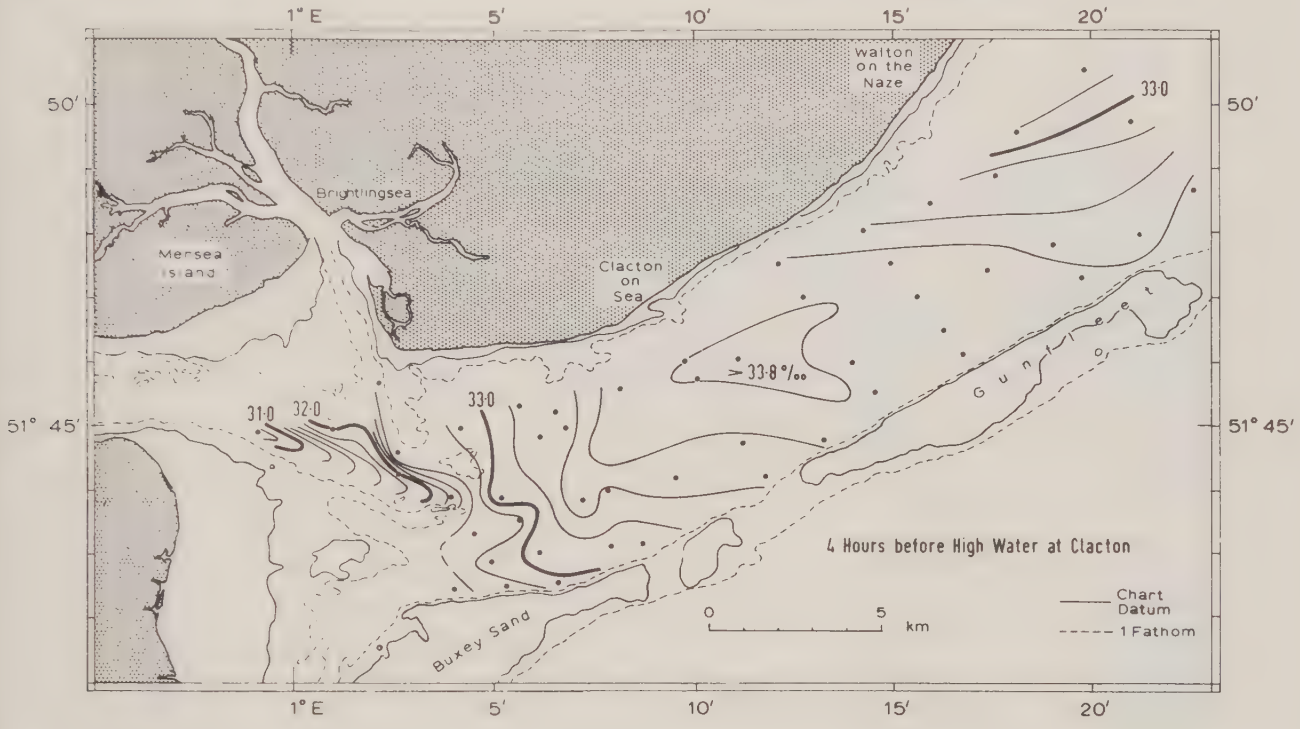
Fig. 51. *Mean surface salinity distribution for low water at Clacton.*



2. *Four hours before high water at Clacton* (*Figure* 52)

This figure shows a marked south-westward movement of the highest salinity water in the central Wallet and a great diminution of its surface area, which may, however, be due to small discrepancies between adjacent observations taken with a ten-day interval between them. An inflow of low-salinity water from the estuary of the Rivers Stour and Orwell is apparent in the north-eastern Wallet. In the west, the $33^0/_{00}$ isohaline has moved roughly 2 kilometres inward towards the Blackwater and Colne estuary. The salinity at the innermost station is now a little below $31^0/_{00}$.

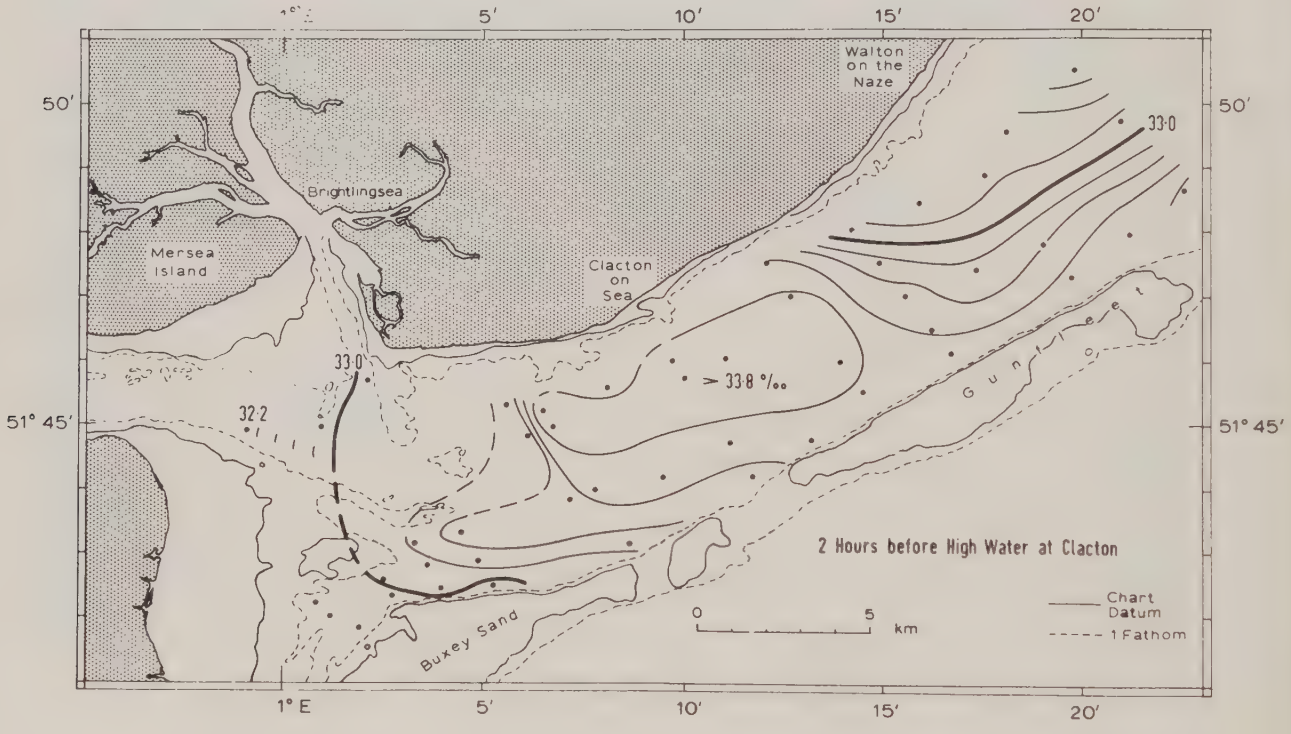
Fig. 52. *Mean surface salinity distribution four hours before high water at Clacton.*



3. *Two hours before high water at Clacton* (*Figure* 53)

The developments noted in the previous figure have continued and the highest salinity water is now centred to the south-east of Clacton. The apparent increase in the area contained by the $33 \cdot 8^0/_{00}$ isohaline may be due to the mixing of offshore water flowing north-westward across the Gunfleet Sand, which will have been largely submerged at this state of the tide; however, this apparent increase may be misleading since, as already discussed, the previous apparent decrease may have been an artefact produced by the combining of non-synoptic data. In the west the $33^0/_{00}$ isohaline extends into the mouths of the Colne and Blackwater and into the entrance of the Ray Sand Channel. Low-salinity water from the Stour and Orwell estuary is present over an increasing area in the north-east Wallet. A salinity of just over $32^0/_{00}$ occurs at the innermost Blackwater station.

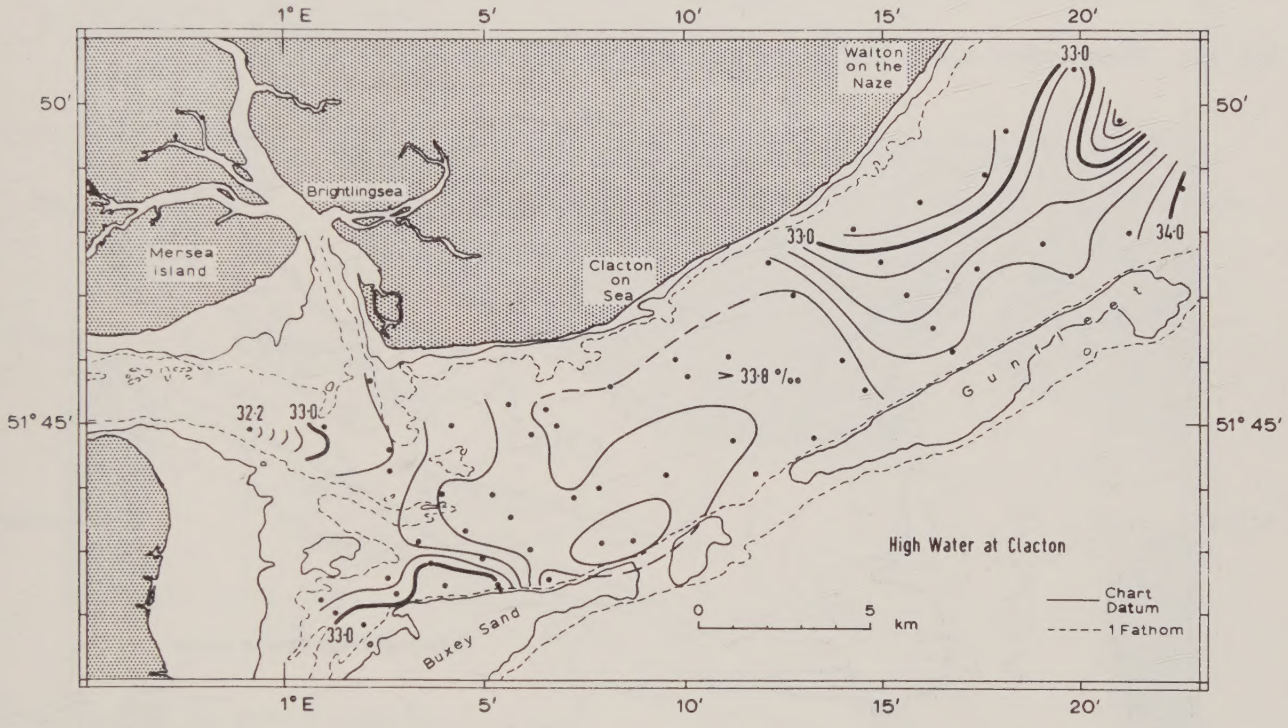
Fig. 53. *Mean surface salinity distribution two hours before high water at Clacton.*



4. *High water at Clacton* (*Figure* 54)

A notable change is shown by comparison with the preceding figures. The water of salinity above $33 \cdot 8^0/_{00}$ in the central Wallet is now connected with offshore water of similar salinity which is entering across the western part of the Gunfleet Sand, and water of salinity greater than $34 \cdot 0^0/_{00}$ has appeared at the easternmost station. The complexity of the $33^0/_{00}$ isohaline in this part of the grid may also reflect increased mixing with offshore water entering the Wallet from across the Gunfleet. The western $33^0/_{00}$ isohaline lies across the lowest reach of the River Blackwater and along the eastern side of the entrance to the Ray Sand Channel, which must be assumed to contain Blackwater and Colne estuarine water now cut off from its parent body.

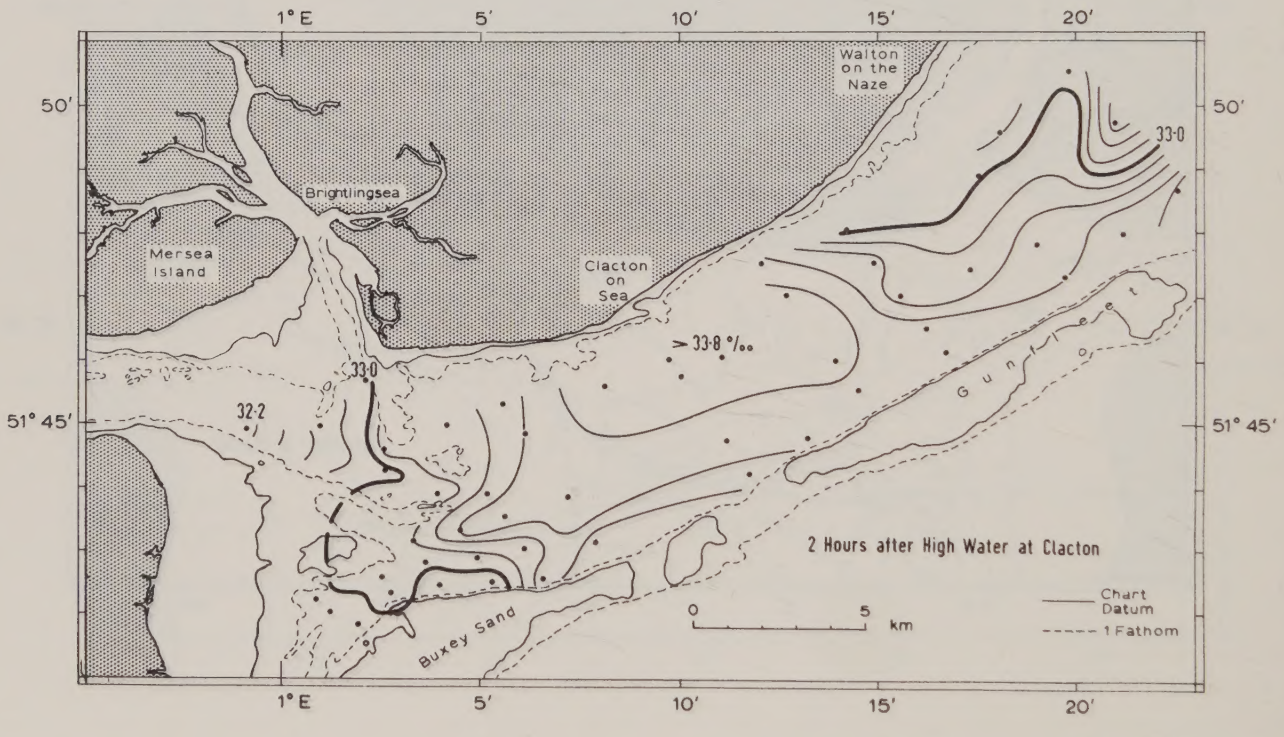
Fig. 54. *Mean surface salinity distribution for high water at Clacton.*



5. *Two hours after high water at Clacton* (*Figure* 55)

Once again the highest-salinity water is isolated from offshore water and conditions are very similar to those existing two hours before high water (Figure 53), although the Stour and Orwell estuarine water has receded somewhat in the north-east Wallet. The salinity at the innermost Blackwater station is at its highest ($32 \cdot 17^0/_{00}$). It might be thought that this was due to a later time of high water in the estuary, but this explanation is considered to be unlikely, since the position at which this maximal salinity was observed is halfway between Clacton and Tollesbury and the Admiralty Tide Tables 1964 show a difference of no more than 33 minutes between the times of high water at these two places. A more likely explanation is that the maximal salinity was caused by evaporation over the extensive mud flats at the sides of the estuary. Weather conditions were favourable for this to occur, and it is probable that there was a delayed salinity maximum similar to that which was observed in the vicinity of the Bradwell nuclear power station during Operation 3 and which, in the main part of this report, has been ascribed to evaporation processes.

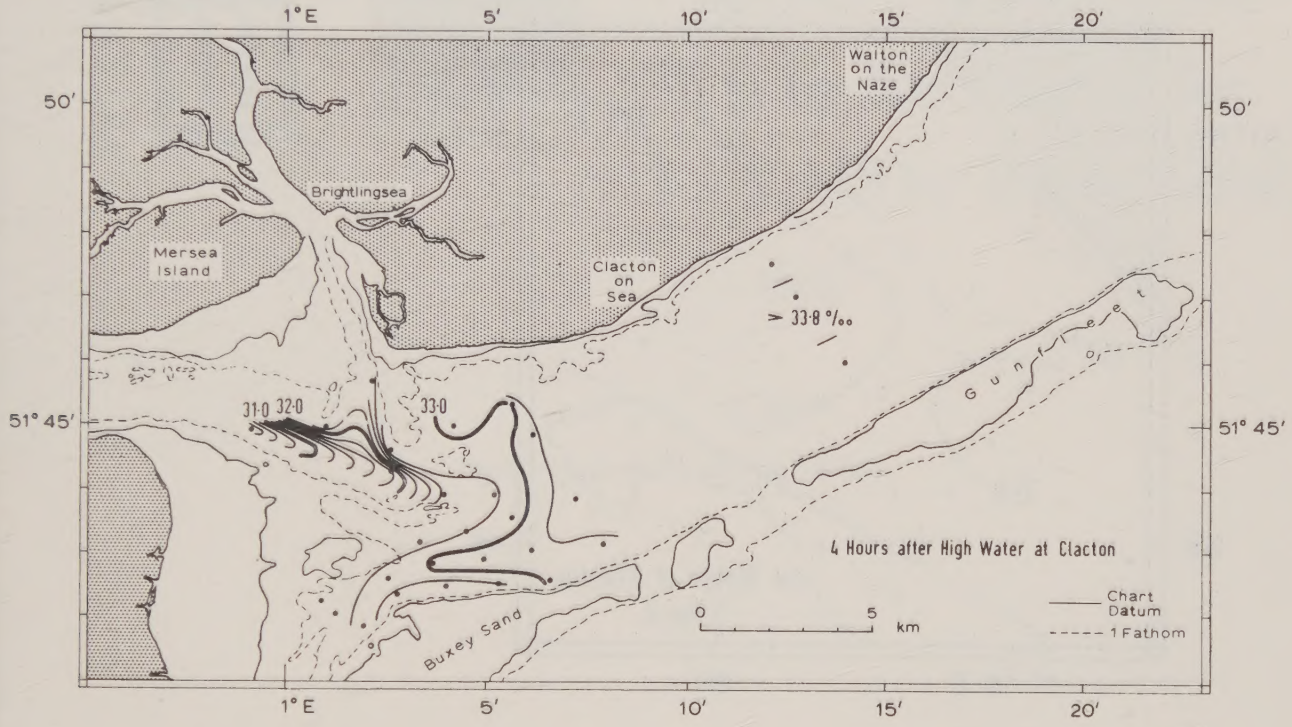
Fig. 55. *Mean surface salinity distribution for two hours after high water at Clacton.*



6. *Four hours after high water at Clacton* (Figure 56)

Few observations were taken at this state of the tide in the Wallet, but in the Blackwater and Colne estuary the general level of salinity is similar to that observed four hours before high water. Water of salinity less than $30 \cdot 4^0/_{00}$ is present in the Blackwater and the outflow from the two rivers has pushed the $33^0/_{00}$ isohaline eastwards over the main estuary channel, leaving a narrow tongue of higher-salinity water in the Ray Sand Channel entrance.

Fig. 56. *Mean surface salinity distribution for four hours after high water at Clacton.*

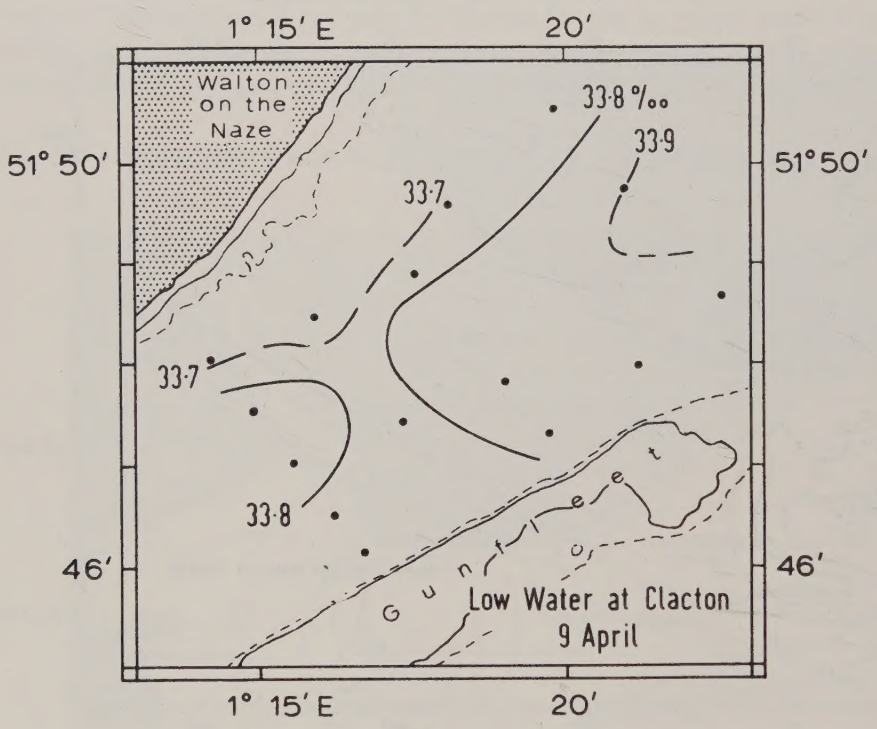


Deviations from the general sequence

A small quantity of data is available to test the degree of confidence which may be placed in Figures 51 to 56 as being representative of conditions over all the ten days of the survey. The most interesting of these are two circuits of the eastern Wallet grid carried out on 9 April at the time of low water. The results are shown in Figure 57 and are in contrast with the situation observed over the same part of the grid on 1 April and shown in Figure 56. Higher-salinity water was present in the east on 9 April and there is little trace of the Stour and Orwell estuarine water which was present on 1 April. As interpreted in Figure 57, the $33 \cdot 8^0/_{00}$ isohaline does not continue across the grid from the east into the central Wallet, but is turned back north-eastwards by a narrow neck of slightly lower-salinity water, thus making the situation in the central Wallet similar in outline to that in Figure 56. On 1 April winds were from the north-east and fresh, and on 9 April they were south-westerly and moderate and hence it seems likely that both distributions are distorted from the mean picture, which must lie somewhere between. As winds during the latter four days of the survey were mostly from between south-west and north-west, in contrast

to the north-easterly winds of 1 April, the isohalines in the eastern Wallet in Figures 51-56 would probably have been found further to the north and east in a truly synoptic survey. Nine isolated observations from the western Wallet on 1 April show that salinities here were about 0·25‰ higher than on 10 April, presumably from the same cause. Changes of this order and the smaller ones found at stations repeated on 7 and 8 April in this area would represent westward displacements of the isohalines by less than 2 kilometres.

Fig. 57. *Surface salinity distribution on 9 April 1964 for low water at Clacton.*



CONCLUSIONS

The results of this survey of surface salinity changes in the Wallet are consistent with the low values for exchange of water between the Blackwater estuary and the sea derived above. They show a comparable low exchange between the Wallet and offshore waters. Renewal of the highest-salinity water in the central Wallet takes place across the western end of the Gunfleet Sand, and over the channels between the Gunfleet and Buxey Sands, around the time of high water. The Blackwater and Colne outflow was found on the south-eastern side of the Wallet, and at the lowest states of the tide it was effectively shut off from the offshore water by the Buxey and Gunfleet sands. The higher-salinity water in the central Wallet moved some 9 kilometres south-westwards between low and high water, and allowed ingress of fresher estuary water from the Stour and Orwell on the landward side of the eastern Wallet, and also of offshore water against the north-eastern extremity of the Gunfleet Sands. It appeared that the Ray Sand Channel contained Blackwater and Colne estuary water at the time of high water and possibly offshore water from the Whitaker Channel (further to the south) at low water.

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